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Environmental risk assessment for non-defuelled, decommissioned nuclear submarines

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The report is a reprint of a subset of the results of a 1998 NATO Pilot Study. Possible accident scenarios involving decommissioned nuclear submarines are discussed. Criticality accidents are found to be the potentially most dangerous events as far as cross-border contamination is concerned. As a case study, the effects of such an accident in North West Russia are evaluated.

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PREFACE

This report constitutes the major part of the NATO report *Environmental Risk Assessment for Two Defence-Related Problems*,[1] which was one of the reports resulting from a pilot study known as *Cross-Border Environmental Problems Emanating from Defence-Related Installations and Activities*. This report was assembled from a number of contributions received from several countries throughout the pilot study. The team members for the study on decommissioned nuclear submarines represented Canada, Denmark, France, Italy, Latvia, the Netherlands, Norway, Russia and the United Kingdom. They are all included as co-authors of this report, and their professional affiliations at the time of the pilot study are listed in Appendix B. The group was chaired by Norway. Efforts were made during study meetings to coordinate the contributions and ensure that they all were based on the same assumptions. However, the reader will discover that in spite of these efforts, the report is not completely consistent in all respects. Reliable information about nuclear submarines is generally hard to obtain, and the inconsistencies shed some light on the uncertainties inherent in all analyses of nuclear submarines.

The report from the study is reprinted here because its evaluation of possible accident scenarios is still quite relevant today, and also because it has never before been published at FFI in spite of the large efforts invested at FFI during its original creation.[2] This publication is made in agreement with the Ministry of Foreign Affairs. The reader should keep in mind that “now,” “presently” and similar expressions in the report refer to 1998.

Kjeller, January 2007

Steinar Høibråten, Ph.D.
Chief Scientist
Chairman of the study group on decommissioned nuclear submarines

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[1] NATO/CCMS Report No. 227, March 1998.

[2] FFI’s participation in the pilot study was financed by the Norwegian Ministry of Foreign Affairs.

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Environmental risk assessment for non-defuelled, decommissioned nuclear submarines

1 INTRODUCTION

This introductory chapter describes the framework within which this study was made. It also contains some general introductory material as well as an outline of the remaining part of the report.

This report is directed towards people working within the broader field of environmental contamination. The readers of chapters other than the first and the last are assumed to be somewhat familiar with scientific texts. However, specialised knowledge about radioactive materials, ionising radiation or submarine design is not required.

1.1 Background

The present case study is one of two case studies that make up Subtopic 4 of Phase II of the NATO/CCMS Pilot Study on *Cross-Border Environmental Problems Emanating from Defence-Related Installations and Activities*. Its history dates back to November 1992 when the North Atlantic Cooperation Council (NACC) launched Phase I of this Pilot Study. In general, the study addresses environmental problems arising from contamination that has crossed international borders. Phase I included chemical and radioactive contamination found in international waters, but was limited to the following geographical areas: the Barents Sea, the Kara Sea, the Baltic Sea, and the Black Sea. The first phase was completed in 1995 [NATO, 1995a; NATO, 1995b; NATO, 1995c].

The Phase I report on radioactive contamination [NATO, 1995a] provided a general overview and quantitative estimate of radioactive sources and contamination of military origin affecting the Baltic, Black and Arctic Seas. The report concluded that the observed levels of contamination are largely due to past practices that are now either discontinued or controlled, such as atmospheric nuclear weapons tests and discharges from reprocessing plants, for example.

Radioactive releases to the Arctic Seas through rivers are relatively small. Until 1991, radioactive waste was routinely dumped into the Arctic Seas. That practice is now discontinued, and the dump sites, despite of their large inventory, neither are nor are expected ever to become a significant source of radioactive contamination.

Among current and potential sources of radionuclide contamination, the process of decommissioning nuclear-powered submarines was identified in Phase I of the Pilot Study as the most important defence-related practice in the Arctic region.

1.2 Phase II

Several sources of potential cross-border contamination were identified at the beginning of Phase II. Among the most significant sources were operating naval propulsion reactors and facilities containing spent nuclear fuel located in the proximity of international boundaries or waters providing an aquatic pathway to those boundaries. Potential risks arising from the operation of nuclear-powered ships and supporting nuclear facilities in their home ports, as well as the risks associated with any presence of nuclear weapons, are beyond the scope of this study. The storage and transport of defence-related spent nuclear fuel are conducted in ways similar to those applying to civilian nuclear fuel. Furthermore, significant international exchanges of information and data on this topic have taken place and continue to take place. Accordingly, the present case study focuses on the potential risks associated with nuclear submarines that have been removed from active service and laid up, or are due to be laid up, for long periods of time (many years) while still containing their spent nuclear fuel.

The decommissioning and dismantling of a nuclear submarine is a very complex process involving a large number of smaller operations. The list of activities that may present a risk of radionuclide contamination includes

- onboard storage of non-defuelled reactors;
- defuelling operations;
- off-loading of fuel to marine transport vessels;
- water transport of fuel storage casks;
- fuel transfer from marine vessels to truck or train transport;
- fuel transport by land to local (temporary) storage facilities;
- fuel transport by special certified trains to reprocessing plants;
- land or waterborne temporary storage of fuel (including damaged fuel); and
- removal and long-term storage of liquid metal cooled reactors.

It is beyond the scope of this study to identify and quantify the entire hierarchy of risks associated with the decommissioning process. The authors of this report have subjectively identified the risks related to certain of the above activities to be of lesser significance than the remaining activities. This identification is based primarily on the anticipated cross-border consequences resulting from accidents that may occur due to the improper conduct of these activities. The list below includes a number of factors that affect the safety of the above activities. If these factors are not satisfactorily resolved, all decommissioning activities could experience a significant increase in accident probability. Relevant factors include

- seaworthiness of marine transport vessels;
- quality of railway track;
- structural integrity of waterborne storage facilities for spent fuel;
- extent of damage to reactors or their fuel;
- availability of safety equipment, quality of the safety programme and rigidity of enforcement;
- quantity and quality of transport casks;
- quantity and quality of dry storage facilities for spent fuel;

- quantity and quality of wet storage facilities for spent fuel;
- quantity and quality of land and waterborne storage facilities for liquid radioactive waste;
- training and qualifications of specialist personnel for defuelling and transfer;
- motivation and safety culture of management and nuclear specialists;
- general socio-economic environment where activity is conducted;
- quality and readiness of emergency planning and protection of the public;
- propensity for human error;
- quality of physical security programme to prevent theft and sabotage;
- regulatory structure, oversight, public knowledge;
- stresses of nature (severe weather, earthquakes, corrosion, fire);
- collision, and other physical damage; and
- quantity and quality of surface, subterranean, or waterborne storage facilities for activated reactor compartments and components.

It should be noted that even defuelled submarines contain significant quantities of radioactive materials in their reactor compartments. These materials have been produced mainly by neutron activation of the reactor vessel and structural components inside it. However, the produced radionuclides (known as *activation products*) are contained inside the steel (metal) matrix and are not mobile. This source of radioactivity should be considered in assessing radioactive waste disposal and evaluating long-term (decades or centuries) aquatic dispersion pathways. As a general rule, 90–99 % of a submarine’s radioactivity is removed when its reactors are defuelled. Further discussion related to defuelled reactor compartments is beyond the scope of this case study.

1.3 Radionuclides and ionising radiation

Radioactive materials emit *ionising radiation* as a result of the decay of unstable atomic nuclei (*radionuclides*). The radiation consists of sub-atomic particles. Ionising radiation can be harmful to living cells, for, as the name implies, its energy is high enough to ionise atoms as it passes through the cells. A number of different radionuclides exist naturally in the environment, but many more kinds have been produced by man in nuclear reactions. The latter are referred to as *anthropogenic* radionuclides.

Irradiation of a cell may cause the cell to die, or it may survive in an altered form called a *transformation*. The transformation may lead to cancer or result in genetic damage to subsequent generations. To some extent, cells have a self-repair mechanism, but some times the repaired cell contains unwanted modifications which may still lead to genetic changes or the reproductive death of the cell. Ionising radiation causes both so-called deterministic and stochastic effects in irradiated tissue. *Deterministic effects* are characterised by a threshold value below which the effect is not observed, and by the fact that the magnitude of a given effect increases with the size of the dose. *Stochastic effects* are effects that occur by chance. Exposure to radiation is generally believed to increase the probability of harmful effects, even at the lowest doses. Radiological protection aims at avoiding deterministic effects by setting effective dose limits below their thresholds. The International Commission on Radiological

Protection (ICRP) has recommended individual dose limits for routine exposures (excluding medical and natural sources) [ICRP, 1991]. As a general principle, any doses should be kept *as low as reasonably achievable*, economic and social factors taken into account (the "ALARA" principle).

There are three categories of ionising radiation from radioactive decay, namely alpha, beta and gamma radiation. *Alpha* (α) *radiation* consists of helium nuclei (alpha particles consisting of two protons and two neutrons) and is mainly emitted by heavy radionuclides (from elements such as uranium and plutonium). The range of an alpha particle is a few centimetres in air and a few tenths of a millimetre in body tissue. Alpha particles cannot, as a rule, penetrate the skin of the human body. However, alpha radiation may cause damage to man if alpha emitters are ingested or inhaled. *Beta* (β) *radiation* consists of electrons and positrons (beta particles). Beta particles are typically stopped by about 0.4 cm of water or about 3 m of air. The range in body tissue is less than 1 cm. *Gamma* (γ) *radiation* consists of photons (gamma particles) and is far more penetrating compared to alpha and beta radiation. It is only partly stopped by a human body, and it is hardly stopped at all by air. However, the intensity of gamma radiation from radioactive decay is typically reduced by 90% by about 30 cm of water. In addition to the above types of radiation, nuclear reactors also generally produce large amounts of *neutron radiation*. As the name implies, neutrons are electrically neutral particles (as are the gamma particles). They are therefore not so easily stopped as alpha and beta particles. See Figure 1.1. For further general information on ionising radiation see, for example, [Shapiro, 1990].

Quantitatively, *radioactivity* (or just *activity*) is expressed by the number of nuclear disintegrations of the given radioactive materials per unit time. This study uses the unit becquerel (Bq) which is the number of disintegrations per second (the older unit curie (Ci) is equal to $3.7 \cdot 10^{10}$ Bq). The activity decreases with time as more and more of the original radionuclides have decayed. The radiological significance of a radioactive source is not just given by its activity, but also by the kind of radiation it emits and the energy of the emitted particles, as well as the chemical properties of the element.

The (physical) *half-life* is the time it takes for the number of radionuclides of a given kind to be reduced to one half of its original value. The half-life may differ dramatically from one radionuclide to the other; it varies from tiny fractions of a second to billions of years. The physical half-life is a characteristic of each radionuclide. Note that the *daughter nuclide* resulting from the decay of a radionuclide is not necessarily a stable nuclide. The decay process often results in another radionuclide, which will eventually decay itself, and so forth. This is known as a *radioactive decay chain*.

As a consequence of radioactive decay, any produced radioactive materials will eventually disappear. However, the half-lives of some radionuclides are so long that they must be considered to be permanently radioactive. In dose assessments, it is common to use the term *effective half-life*. This is the time it takes to reduce the activity of a given kind of radionuclide in the body to one half of its original value. The effective half-life is shorter than the physical

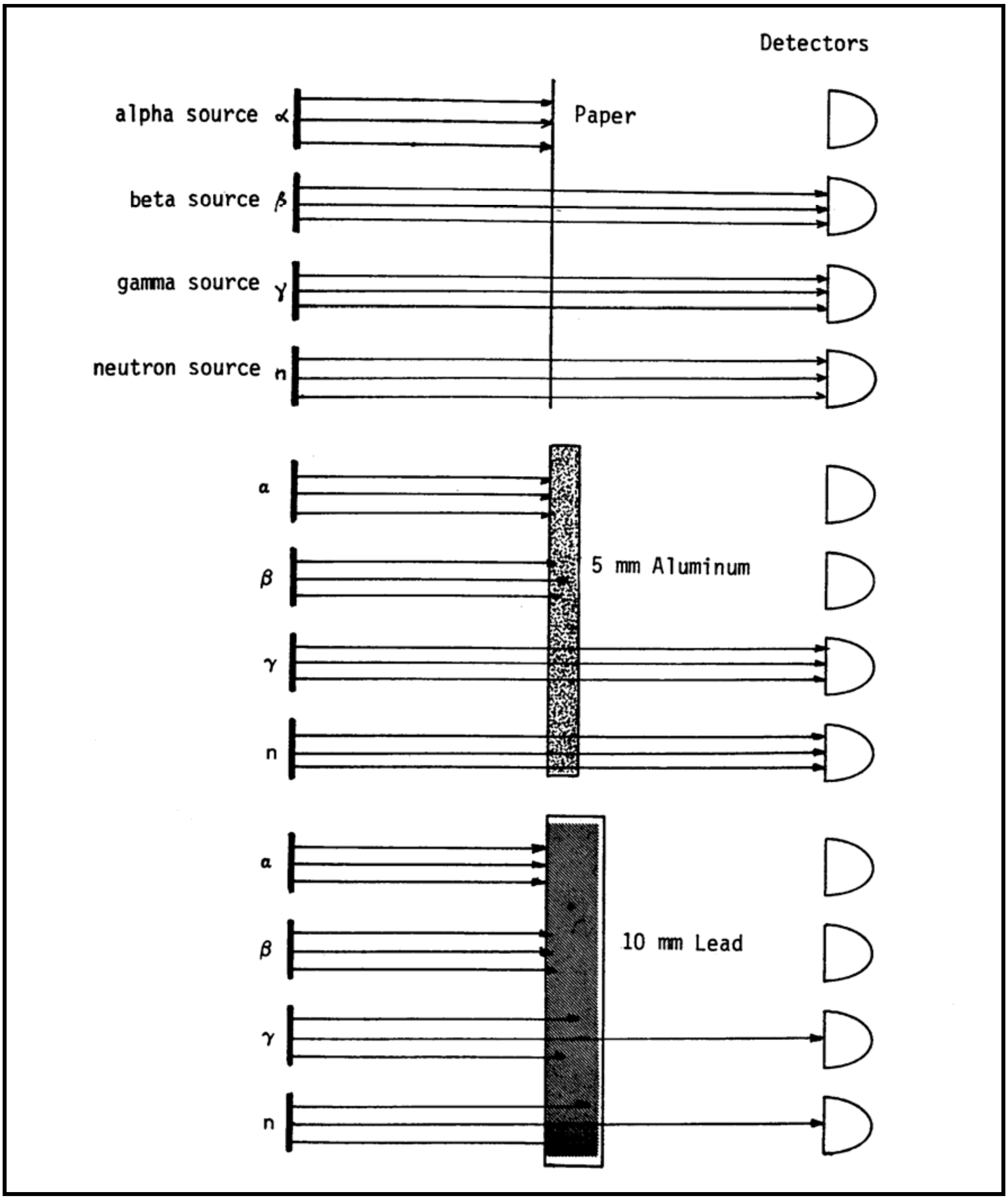

Figure 1.1. The penetrating powers of alpha, beta, gamma and neutron radiation (after [Burnham, 1986]). Alpha and beta radiation are easily stopped, while complete shielding from gamma and neutron radiation is practically impossible to achieve.

half-life because the body's natural replacement of the element is also included. The effective half-life is not necessarily constant in time, and it may be reduced by the administration of various chemicals.

A nuclide is the nucleus of an atom and consists of a number of *protons* (which have a positive electric charge) and *neutrons* (which are neutral). In a complete atom, this nucleus is surrounded by (negatively charged) *electrons* which balance the charge of the nucleus, and

Table 1.1. Standard prefixes used to express decimal fractions and multiples.

Prefix	Symbol	Factor	Prefix	Symbol	Factor
yocto	y	10^{-24}	deca	da	10^{1}
zepto	z	10^{-21}	hecto	h	10^{2}
atto	a	10^{-18}	kilo	k	10^{3}
femto	f	10^{-15}	mega	M	10^{6}
pico	p	10^{-12}	giga	G	10^{9}
nano	n	10^{-9}	tera	T	10^{12}
micro	µ	10^{-6}	peta	P	10^{15}
milli	m	10^{-3}	exa	E	10^{18}
centi	c	10^{-2}	zetta	Z	10^{21}
deci	d	10^{-1}	yotta	Y	10^{24}

which are responsible for all chemical interactions. A nuclide of chemical element X is generally denoted as ^{A}X where A is the *mass number* (that is, the total number of protons and neutrons in the nucleus). Occasionally, the letter *m* is added to the mass number; this indicates that the nuclide is in an *isomeric state*, that is, a relatively long-lived state different from the regular *ground state* of the nuclide. Each specific chemical element is determined by the number of protons in its atomic nucleus. However, several different nuclides, differing only in their number of neutrons, have been observed for all elements. Such nuclides are known as different *isotopes* of the element in question. Usually only one or just a few of these isotopes are stable.

1.4 Units and prefixes

As in all modern scientific texts, SI units (*Système International d'Unités*) are consistently used throughout this report. The Bq has already been defined above, and other units will be introduced as needed. In addition, the unit *tonne* is used in places. It denotes a metric tonne (that is, 1000 kg).

Often either a small fraction of a unit quantity or a very large number of such units must be referred to. This is commonly done by using the standard prefixes listed in Table 1.1. Many of these prefixes occur throughout this report, for example, 1 TBq = 10^{12} Bq.

1.5 Report structure

Contributions to this report have been made by several individuals and groups. The structure of the report is necessarily somewhat shaped by these contributions; however, the general structure has also been used to provide basic outlines for the contributions.

Chapter 2 defines the nature and magnitude of the problem of decommissioning nuclear submarines. First, an overview is given of the number of nuclear submarines belonging to the various nuclear powers; second, a brief description of nuclear propulsion systems in general is provided; third, the decommissioning process in several countries is described; and fourth, a description of the location and the state of those nuclear submarines that have been laid up with their spent nuclear fuel still inside their reactor vessel(s) is presented.

Chapter 3 describes the potential ways and means that could lead to cross-border radionuclide contamination, as well as the analysis models used to assess the radioactive risk.

Chapter 4 contains detailed analyses of the most probable accident scenarios. Two events are assessed in detail: a core heat-up event, which could result from a coolant leak, or a disruption in the decay-heat removal process; and a core criticality accident (also known as a recriticality or reactivity accident), which could occur during the defuelling process.

Chapter 5 describes the radioactivity dispersion analysis and its results for aquatic and atmospheric dispersion.

Chapter 6 provides a brief summary of the study as well as its conclusions and recommendations.

All references are listed in Chapter 7.

2 DECOMMISSIONING OF NUCLEAR SUBMARINES

Since the mid-1950s the nuclear-weapons powers, particularly the United States and the Soviet Union/Russia, have built large naval forces propelled by nuclear power. For many years one could build nuclear submarines without having to retire any of them, but as more and more of them conclude their useful service life, the problem of handling retired submarines becomes more pressing. The term *decommissioned submarine* appears to be used differently in different contexts. In this report it refers to any submarine that has been taken out of service with the intention of never again being returned to active duty.

The magnitude of the problem was initially addressed in Phase I of the Pilot Study [NATO, 1995a], and part of the general description below is taken from that study. The reader may wish to consult [NATO, 1995a] for a more comprehensive review.

2.1 Nuclear submarines

Conventionally-powered submarines run on battery power when submerged and on diesel-electric power when at or near the surface. The latter process, which also recharges the batteries, requires a supply of outside air. As a consequence, conventional submarines are significantly limited by the batteries as to the time they can stay submerged. Nuclear reactors on the other hand do not require oxygen to run, allowing them to operate submerged for very long time periods. This gives nuclear-powered submarines a vastly superior endurance.

Table 2.1. Nuclear submarines built and retired world-wide as of January 1998 [Handler, 1998]. SSBN stands for nuclear ballistic missile submarines, SSGN stands for nuclear cruise missile submarines, and SSN stands for nuclear fleet submarines (usually attack submarines). "Out of service" does not include submarines sunk at sea, used as training ships or converted from one type to another.

Country	Total built Jan. 1998	In service 1989–90	In service Jan. 1998	Out of service 1989–90	Out of service Jan. 1998
China	**6**	**5**	**6**	**0**	**0**
• SSBN	1	1	1	0	0
• SSN	5	4	5	0	0
France	**13**	**6**	**10**	**0**	**3**
• SSBN	7	6	4	0	3
• SSN	6	0	6	0	0
Russia	**248**	**197**	**77**	**20**	**167**
• SSBN	91	72	27	15	63
• SSGN	60	51	12	1	48
• SSN	92	74	34	4	55
• Other	5	0	4	0	1
United Kingdom	**26**	**20**	**15**	**1**	**11**
• SSBN	7	4	3	0	4
• SSN	19	16	12	1	7
United States	**191**	**134**	**94**	**24**	**95**
• SSBN	59	38	22	12	37
• SSN	131	95	71	12	58
• Other	1	1	1	0	0
Total world-wide	**484**	**362**	**202**	**45**	**276**

Furthermore, they are generally designed such that they can operate for a very long time before refuelling is required, typically some 7–15 years.

The first nuclear submarine was the *USS Nautilus* which was launched in 1954. The Soviet Union followed suit in 1957 with *K-3* (later named *Leninskiy Komsomol*) of the Project 627/November class. Other nations operating nuclear submarines include the United Kingdom (since 1963), France (since 1969) and China (since 1974). The American nuclear naval fleet reached its highest number of operational vessels in 1987–1988, the Russian nuclear fleet in 1989 and the British nuclear fleet in 1990. As of January 1998, there were 202 nuclear submarines in operation in the world, while a total of 276 submarines (corresponding to 419 nuclear reactors) had been taken out of service [Handler, 1998]. See Table 2.1 for further details.

Nuclear submarines are categorised according to their use. The strategic submarines carrying ballistic missiles are usually designated SSBN, those carrying nuclear guided or cruise missiles SSGN and fleet submarines (attack submarines) SSN.

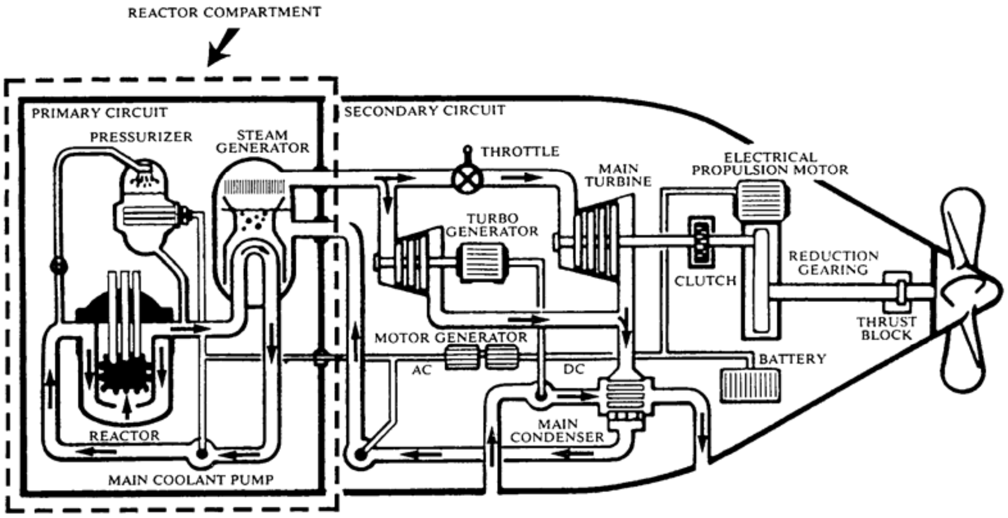

Figure 2.1. Nuclear propulsion system. From [House of Commons, 1989].

A large number of books (for example, [Arkin and Handler, 1989; Dukert, 1973; Eriksen, 1990; Jane's 1997; Nilsen *et al.*, 1996; Pavlov, 1997]), articles and naval handbooks contain information on naval nuclear ships. However, much of this information is unreliable since it is based on "guesstimates" rather than on facts and exact design information. This is hardly surprising since naval authorities for obvious reasons do not wish to reveal strengths and weaknesses of their nuclear ships to potential adversaries. Therefore, the analyses that are made in this study are often based on parameter values estimated by the authors as opposed to officially supplied by the respective navies.

2.2 Nuclear propulsion systems

A nuclear propulsion system is sketched in principle in Figure 2.1. The primary circuit containing the reactor coolant is completely enclosed in the submarine's reactor compartment. The predominant reactor type for naval propulsion is the pressurised water reactor (PWR). A particular advantage of the PWR is that for a given power level, it can be designed with a small core because of water's excellent ability to moderate (slow down) neutrons. A small, compact reactor (including shielding) with a high power density is obviously of great importance for submarines where space requirements are crucial. The liquid metal cooled reactor (LMR) has a higher power density and is even more compact than the PWR. The United States has built one submarine with a sodium cooled reactor, and the Soviet Union built a total of less than ten submarines with lead-bismuth cooled reactors. The difficulties of operating LMRs (such as the risk of solidification of the coolant) appear to outweigh the benefits, however, and modern submarines are not equipped with such reactors.

Nuclear submarines are fuelled with highly enriched uranium. The enrichment indicates the fraction of the uranium isotope ^{235}U in the total amount of uranium (consisting of ^{235}U and ^{238}U). Depending on reactor design, the enrichment varies from about 20% to more than 90% [OTA, 1995; Eriksen, 1990]. In the reactor, the fuel is arranged in fuel assemblies. Naval reactor cores probably consist of a few hundred of these (say 100–300 or so). Fuel assemblies for civilian power reactors consist of a number (several tens) of fuel rods. Information about the arrangement of the nuclear fuel within naval reactors is not openly available, but a typical reactor core with fresh fuel may contain in the realm of 200 kg of ^{235}U [Eriksen, 1990].

2.3 National decommissioning practices

While the life-cycle of nuclear-powered submarines is similar to that of other nuclear installations, the submarines are governed by a separate regulatory regime which in general is closed to public scrutiny. Hence it is difficult for the public to properly assess the practices employed for decommissioning activities, including storage and disposal of radioactive waste.

Generally, the decommissioning strategy applied to a specific nuclear technology is determined by the consideration of many factors. In the civilian domain, decommissioning guidance is available from the International Atomic Energy Agency (IAEA) [IAEA, 1990]. After bringing a facility to a final, safe, shut-down condition, the facility owner prepares a decommissioning plan describing the facility itself, the rationale for the adopted strategy, the decommissioning schedule, tools and procedures to be used, the safety assessment addressing normal and abnormal situations that may arise during decommissioning, the environmental impact, the radiation protection program, the quality assurance program, the emergency plans, the resource requirements and allocation, and so forth. Decommissioning activities produce large quantities of waste; hence, the selected strategy must include ways to minimise the waste and to transport it to safe storage facilities for its ultimate disposal.

In the case of nuclear submarines, the decommissioning strategies differ from one country to the next. Four of the five countries listed in Table 2.1 have by now decommissioned some of their nuclear submarines. (The Chinese nuclear navy is still comparatively young; consequently, no Chinese vessels have yet been retired.) The number of retired submarines has grown dramatically during the 1990s, from 45 in 1989–1990 to 276 at the beginning of 1998 [Handler, 1998]. As a result of the general secrecy on naval nuclear propulsion systems, the degree of openness about any nation’s decommissioning practices is limited. However, all four countries in question have over the years made public some information about their decommissioned submarines. An overview of the decommissioning process in these countries follows below.

2.3.1 The United States

With *USS Nautilus* in 1954, the United States became the first country to operate a nuclear-powered submarine. Table 2.1 shows that by January 1998, a total of 95 nuclear submarines had been retired from the United States Navy. The Navy has developed and implemented a program to safely dispose of its decommissioned nuclear submarines [United States Navy, 1993]. This program includes defuelling the reactor, inactivating the submarine, removing the reactor compartment for land disposal, cutting up the remainder of the submarine and recycling or disposing of the materials as appropriate.

Planning for the decommissioning of nuclear submarines and the disposal of their reactor compartments began in the late 1970s. This process ended in an environmental impact statement [United States Navy, 1984] which led the United States Navy to conclude that "Based on consideration of all current factors bearing on a disposal action of this kind contemplated, the Navy has decided to proceed with disposal of the reactor compartments by land burial." The reactor compartments have since been taken to the Department of Energy's disposal grounds at Hanford, Washington.

The *USS Triton* became the first decommissioned American nuclear submarine in May 1969 [Handler, 1998]. The number of decommissioned submarines remained very low until about 1980 when the Navy began retiring ballistic missile submarines as a result of SALT II Treaty limits. At that time, a retired submarine was first "inactivated" (that is, weapons systems and loose equipment were removed, temporary ventilation, lighting, power and compressed air systems were installed, and the reactor was defuelled), then the missile compartment of the submarine was dismantled, the remaining parts of the submarine were welded back together, and the vessel was placed in floating storage. Since the mid-1980s, the reactor compartments have been removed in parallel with the dismantling of the missile compartments, and since 1991, missile compartment dismantlement, reactor compartment removal and ship recycling have been carried out in one single dry-docking evolution at the Puget Sound Naval Shipyard in the state of Washington.

The nuclear reactors in American submarines are all rugged and compact pressurised water reactors designed to withstand both severe power transients and the shocks of battle. After the spent nuclear fuel has been removed, more than 99% of the radioactivity is also removed. Approximately 99.9% of the remaining activity is then found in activation products in the structural metals forming the plant components. The remaining activity is in the form of radioactive corrosion and wear products which have been deposited on the inside of piping systems. The most important activation product is ^{60}Co with a half-life of 5.27 years. Experience shows that the external radiation levels on the hull of the reactor compartments are relatively low: no more than 300 μSv/h at any given location and for the most part below 10 μSv/h.

The reactor compartments are transported by barges on the Columbia river from the Puget Sound Naval Shipyard to the Hanford site. At the Hanford site they are stored intact in an open trench in the desert as shown in Figure 2.2. Here they will remain in the open for the foreseeable future. There are no plans to further dismantle them. A corrosion study of the reactor compartments in the Hanford desert has concluded that at least 600 years will pass before some lead, as the first of the hazardous substances inside, will be able to escape. Radioactivity will remain contained far longer because the radioactive metal alloys are highly resistant to corrosion in the Hanford soil and will tend to resist the formation of transportable corrosion products [Naval Civil Engineering Laboratory, 1992].

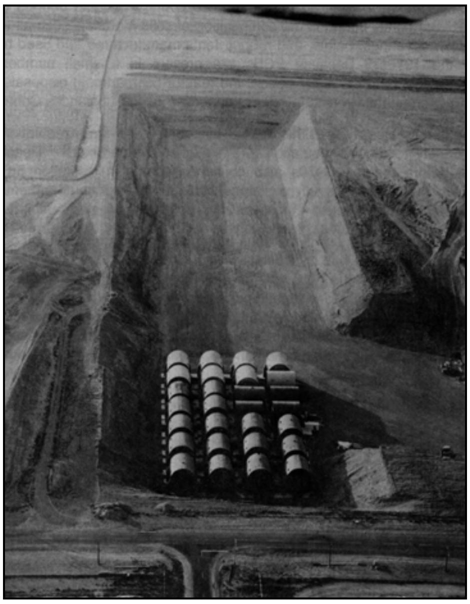

Figure 2.2. The storage trench for reactor compartments removed from decommissioned American nuclear submarines at the Hanford site in Washington. The picture is from about 1993 when 28 reactor compartments were stored here [United States Navy, 1993]. At the end of 1996, 61 reactor compartments were stored in the trench [Hanf et al.*, 1997].*

The cost of decommissioning an American nuclear submarine is reportedly around 35 million USD.

2.3.2 Russia

In 1957, the Soviet Union launched its first nuclear submarine, the *K-3* (later named *Leninskiy Komsomol*) of the Project 627/November class. Since then, close to 250 more nuclear submarines have entered service in the Soviet/Russian Navy. These submarines have been distributed between the Northern Fleet and the Pacific Fleet. Many of the vessels are now past their useful service life, or they have been scrapped as a result of international disarmament treaties. The Project 645/modified November class submarine *K-27* was the first to be retired (due to a major reactor accident in 1968). As of January 1998, an estimated 167 submarines were retired, up from about 20 submarines in 1990 [Handler, 1998].

Russian decommissioned nuclear submarines are presently treated in one of two different ways. This is described in a comprehensive study that was commissioned by the Royal Ministry of Foreign Affairs in Norway [Kværner, 1996]:

1. The submarine is first prepared for prolonged waterborne storage. This is followed by storage afloat of the entire vessel including the reactor compartment (in the case of ballistic missile submarines, the missile compartment is removed, and the remaining fore and aft sections are welded together).
2. The reactor compartment is removed along with (parts of) its neighbouring compartments as a three-compartment unit. This unit is prepared for waterborne storage and subsequently stored afloat. The remaining hull sections are scrapped.

Preparation for prolonged waterborne storage involves the following operations:

a) At the pier:
- removal of spent nuclear fuel;
- emptying the primary and secondary circuits of the power plant;
- radiological survey;
- emptying and drying of radiation protection tanks;
- emptying of fuel and oils, and cleaning the tanks by steaming;
- inactivation of contaminated sections;
- collection of radioactive waste;
- final radiological survey.

b) On the slipway:
- unloading of equipment and dismantling of superstructure;
- securing water tightness of hull;
- preparation for towing.

The hull is then launched, towed to the storage location and moored.

The more complete scrapping procedure includes removal of the reactor compartment. The steps at the pier remain the same, while the tasks at the slipway are:
- cutting out the three-compartment reactor unit;
- dismantling all equipment, piping and cabling from the hull;
- cutting the hull in large sections (typically 30 tonnes) to be moved elsewhere.

The three-compartment reactor unit is further prepared for storage adjacent to the slipway:
- dismantling of all equipment in the compartments adjoining the reactor compartment;
- dismantling of superstructure and coatings;
- installing new or strengthening existing bulkheads, sealing off the compartments;
- securing water tightness of the pressure hull (the inner hull of a Russian submarine) and bulkheads;
- preparing for towing.

The three-compartment unit is then launched, towed to the storage location and moored. It is reportedly prepared for up to about 10 years of waterborne storage.

Eventually, plans call for the reactor compartments themselves to be removed from the three-compartment units and placed in dry storage. This has not yet began to happen, and it is probably still a few years into the future.

The scrapping of a Russian nuclear submarine is reported to cost some 3–4 million USD [Handler, 1998].

Table 2.2. Decommissioned submarines of the Russian Northern Fleet as of September 1, 1995 [Kværner, 1996]. Both the number of submarines (Subs) and the number of reactors (Reac.) are listed. The Russian project number as well as the Western class designation is given. SSN stands for nuclear fleet submarine, usually attack submarine, SSBN stands for nuclear ballistic missile submarine, and SSGN stands for nuclear cruise missile submarine. The reactors are either pressurised water reactors (PWR) or liquid metal reactors (LMR).

Project/Class	Type	Built	Reactor	Decommissioned submarines			
				Defuelled		Non-defuelled	
				Subs	Reac.	Subs	Reac.
627/November	SSN	1958-63	PWR	1	2	7	14
658/Hotel	SSBN	1958-62	PWR	2	4	3	6
661/Papa	SSGN	1971	PWR			1	2
667/Yankee/Delta	SSBN	1967-present	PWR	7	14	12	24
670/Charlie-II	SSGN	1973-80	PWR	1	1	2	2
671/Victor	SSN	1967-92	PWR	1	2	11	22
675/Echo-II	SSGN	1961-68	PWR	2	4	13	26
701/Hotel-III	SSBN	1958-62	PWR			1	2
705/Alfa	SSN	1970-83	LMR	4	4	2	2
Total				**18**	**31**	**52**	**100**

As of 1995, the Northern Fleet had nine submarines ready for prolonged waterborne storage with another five in preparation; six submarines were in waterborne storage as three-compartment units, and another ten were in preparation; and four submarines were being scrapped [Kværner, 1996]. Taking into account that as of September 1, 1995, 70 nuclear-powered submarines had been officially decommissioned from the Northern Fleet (cf. Table 2.2), it is clear that there is a significant backlog of decommissioned, but not yet defuelled, submarines. Officially as of the same date, there were 52 non-defuelled, decommissioned submarines at the Northern Fleet alone.

For comparison and further information, Table 2.3 lists the number of laid-up submarines of the Northern Fleet at the end of 1995 as reported in a recent Russian report [Khlopkin *et al.*, 1997]. The differences in the reported numbers between Table 2.2 and Table 2.3 are probably due to the different sources used, the slight difference in time, and in particular the fact that Table 2.2 lists officially decommissioned submarines while Table 2.3 seems to list all laid-up submarines (including those that have been taken out of service, but not yet officially decommissioned).

2.3.3 The United Kingdom

The Royal Navy’s first nuclear submarine, the *Dreadnought*, was decommissioned in 1982 after 19 years of service, and since then another ten submarines have been taken out of service (cf. Table 2.1). Some of the concerns over the final disposal of this and other nuclear submarines are documented in [House of Commons, 1989]. Three options were considered for

Table 2.3. Laid-up nuclear submarines of the Russian Northern Fleet at the end of 1995 [Khlopkin et al., *1997]. Both the number of submarines (Subs) and the number of reactors (Reac.) are listed. The Russian project number as well as the Western class designation is given.*

Project/Class	In operation	Submarines stored afloat			
		Defuelled		Non-defuelled	
		Subs	Reac.	Subs	Reac.
Submarines of the first generation					
627, 627A / November	1958-89	2	4	6	12
658, 658M, 701 / Hotel	1960-89	3	6	3	6
675, 675MK / Echo-II	1963-92	2	4	12	24
661 / Papa	1970-88			1	2
Subtotal first generation		*7*	*14*	*22*	*44*
Submarines of the second generation					
667A, 667AT, 667AY, 667M / Yankee	since 1967	9	18	9	18
667B / Delta-I	since 1972			7	14
667BD / Delta-II	since 1975			4	8
667BDR / Delta-III	since 1976			1	2
667BDRM / Delta-IV	since 1985				
670M / Charlie-II	1975-96	1	1	5	5
671 / Victor-I	1967-91	1	2	11	22
671RT / Victor-II	since 1971			5	10
671RTM / Victor-III	since 1978				
705 / Alfa	1971-95	4	4	3	3
Subtotal second generation		*15*	*25*	*45*	*82*
Total first and second generation		**22**	**39**	**67**	**126**

the disposal of reactor compartments: (1) dumping at sea; (2) shallow burial on land at a coastal site; and (3) disposal in a deep geological repository. The last option involves cutting up the reactor compartment into pieces that can fit inside storage containers about 1.7 m×1.7 m×1.15 m size.

An environmental impact study of the three options is also included in [House of Commons, 1989]. Here it was found that the collective dose commitment to the public would be an estimated 43–45 manSv for option (1), $3{\cdot}10^{-6}$–35 manSv for option (2) and $5{\cdot}10^{-4}$–$8{\cdot}10^{-3}$ manSv for option (3), and that the collective dose to the workers preparing for disposal would be an estimated 0.7 manSv, 1.4 manSv and 10 manSv, respectively.

The British government has issued a statement to the Pilot Study about its present decommissioning practices [United Kingdom, 1996]. In its entirety, the statement reads:

> “The UK Government’s present policy is that decommissioned nuclear-powered submarines should be stored safely afloat at the location where they are decommissioned. The perceived final disposal route is the planned Deep Repository to be developed by NIREX early next century. The timetable for the construction of the NIREX Repository assumes an availability date of 2012.
>
> “As soon as practicable after leaving service a decommissioned nuclear submarine undergoes Defuel, De-equip and Lay-up Preparation (DD&LP). During DD&LP the used fuel is removed and sent for storage; the hull is then prepared for a period of storage afloat at the DD&LP yard. At the end of DD&LP the vast majority of residual radioactivity is contained within the Reactor Compartment. The laid up submarines remain subject to routine checks including radiation monitoring, the results of which are provided to the relevant local authority. In addition, routine maintenance is conducted, including a docking every ten years. As of July 1996, seven submarines have undergone DD&LP; four of these are stored afloat at Rosyth and three at Devonport. It is envisaged that after a period of storage each submarine will be dismantled and the Intermediate Level Waste (ILW) will be sent to the NIREX repository. A period of storage reduces the ILW arisings and reduces the dose burden associated with dismantling and packaging the waste.”

According to [House of Commons, 1989], the spent fuel is sent to Sellafield in Cumbria for storage. The *Dreadnought*, which was the only decommissioned nuclear submarine in 1989, was treated with a protective paint and equipped with a cathodic protection system to further inhibit corrosion. It was expert opinion at the time that with regular survey and repainting, the vessel could remain afloat for hundreds of years if necessary. The radiation level on the hull of the *Dreadnought* just above the reactor compartment was about 5 μSv/h in 1989 [House of Commons, 1989].

The decommissioning of a submarine in the United Kingdom costs about 17–30 million USD [Handler, 1998].

2.3.4 France

As of late 1997, only the very first French nuclear submarine, *le Redoutable* from 1969, had been decommissioned (1991) and dismantled, while a second submarine was undergoing decommissioning procedures. However, owing to the long French commitment to nuclear energy, and to its extensive use especially for power generation, the total number of decommissioned nuclear installations of various kinds on French territory is already large.

The steps of dismantling nuclear installations are not defined by French law, but the practice is in accordance with IAEA recommendations. French strategy for the dismantling of nuclear ships complies in every way with the same recommendations. The nuclear fuel is first unloaded in a similar way as it was done several times during the active service of the ship. The reactor compartment is then isolated and separated from the rest of the submarine. It is subsequently emptied of all removable equipment (such as rotating machines, electrical equipment, and so on), small diameter piping and combustible materials. Pipes and vessels remaining in the compartment are emptied and dried. The primary circuit is sealed off.

The purpose of these operations is:

- To avoid any risk of deterioration of the reactor compartment and of what it still contains during the interim storage period, particularly by preventing corrosion and fire;
- To guarantee an excellent containment of the residual radioactivity with respect to the environment. This containment consists of two tight barriers: the primary circuit and the reactor compartment.

All front and rear bulkhead passages of the reactor compartment are sealed off. The submarine hull is cut off beyond these bulkheads to obtain a tight cylinder, closed at each end. A system for sampling the air contained in the reactor compartment has been provided so that periodic monitoring of the activity can take place.

The reactor compartment of the *le Redoutable* is now, after conditioning as described above, being stored in the Cherbourg naval shipyard. The intention is to keep it there for a total of 15 to 20 years to allow significant decay of the remaining radioactivity. A secluded location protected from sea and weather has been designated for this reactor compartment and others to come. Ultimately, the reactor compartment will be fully dismantled and the resulting waste conditioned for storage by the National Agency for the Management of Radioactive Waste (ANDRA).

The remaining aft and fore sections of the submarine are welded together, and all circuits that have contained radioactive fluids are removed. The hull can then be treated like that of any other ship that has been decommissioned from active service.

Spent nuclear fuel discharged from submarines, either during their active service or after decommissioning, is managed in the same way as fuel from research or prototype reactors:

- After defuelling, it is first stored in a pool for cooling for a period of 5–20 years;
- It is then encapsulated in canisters and transferred to a dry storage facility;
- Its ultimate future is undecided as yet. As for other spent nuclear fuel, the final step could be either reprocessing or conditioning and disposal in a deep repository.

The French Atomic Energy Commission (CEA) has built a specialised facility for interim storage of spent nuclear fuel from research, prototype and naval reactors. This facility, named CASCAD and located at Cadarache in Provence, has been in operation since 1990.

The cost of decommissioning and dismantling a nuclear submarine in France is about 20 million USD.

2.3.5 Comments on decommissioning practices

The above presentation of decommissioning practices shows that all four nuclear powers who are presently decommissioning nuclear submarines have procedures and plans for how to dismantle the submarines and dispose of the resulting radioactive waste products. In all countries except Russia, removal of the spent nuclear fuel takes place before the vessel is put into short-term storage to await further dismantling.

In general, the defuelling operation greatly improves the nuclear safety of the decommissioned reactors in two respects:

1. Fundamentally, the core of a reactor is a critical array, and it may release large amounts of energy at any moment should its safety features fail. Once defuelled, the reactor becomes a completely passive component. (The storage facility to which the fuel has been transferred is of course designed to remain subcritical under any event.) Defuelling does not prevent all risk, but accidental radionuclide contamination of the surrounding environment can subsequently be caused only by external events (fire, sinking, and so forth).

2. Defuelling minimises the amount of radionuclides on board the submarine by a factor on the order of 100. Moreover, the remaining activity is mainly due to ^{60}Co and ^{55}Fe which are contained in the activated steel. As such, the release into the environment is likely to be slow and localised.

Recognising these points, the IAEA has recommended early defuelling for all permanently shut down reactors [IAEA, 1997d]. In case of particular difficulties (for instance, a damaged core or a core of special design), the operator should propose alternative safety procedures and be licensed for applying these to the non-defuelled reactor.

2.4 Non-defuelled, decommissioned submarines

As follows from the discussion in Section 2.3, this particular case study mainly applies to Russian decommissioned nuclear submarines, some of which have been awaiting defuelling for 5–10 years or even longer. This section provides further details about Russian decommissioned submarines.

2.4.1 Location of submarines

Both the Pacific Fleet and the Northern Fleet of the Russian Navy operate nuclear submarines, and both have a number of moored, non-defuelled, decommissioned submarines awaiting further processing. The figures cited below relate only to the larger Northern Fleet, but similar conditions also exist at the Pacific Fleet.

As a rule, decommissioned submarines are moored at the bases from which they were operating. They are therefore somewhat scattered around the Kola Peninsula and Severodvinsk as shown in Table 2.4 and on the map in Figure 2.3. Table 2.4 shows the

Table 2.4. Location and number of decommissioned submarines of the Russian Northern Fleet as of September 1, 1995 [Kværner, 1996]. The numbers correspond to those listed earlier in Table 2.2.

Location	Decommissioned submarines		Non-defuelled submarines
	Total	Non-defuelled	
Zapadnaya Litsa Bay	2	1	1 Project 705/Alfa
Ara Bay	6	6	1 Project 670/Charlie-II 5 Project 675/Echo-II
Ura Bay	7	7	1 Project 670/Charlie-II 6 Project 675/Echo-II
Saida Bay	8	1	1 Project 667/Yankee/Delta
Olenia Bay	5	3	1 Project 658/Hotel 1 Project 667/Yankee/Delta 1 Project 675/Echo-II
Polyarny	8	8	3 Project 627/November 1 Project 658/Hotel 3 Project 671/Victor 1 Project 675/Echo-II
Gremikha	13	13	4 Project 627/November 1 Project 658/Hotel 8 Project 671/Victor
Severodvinsk	20	12	1 Project 661/Papa 10 Project 667/Yankee/Delta 1 Project 705/Alfa
Murmansk	1	1	1 Project 701/Hotel-III
Total	70	52	

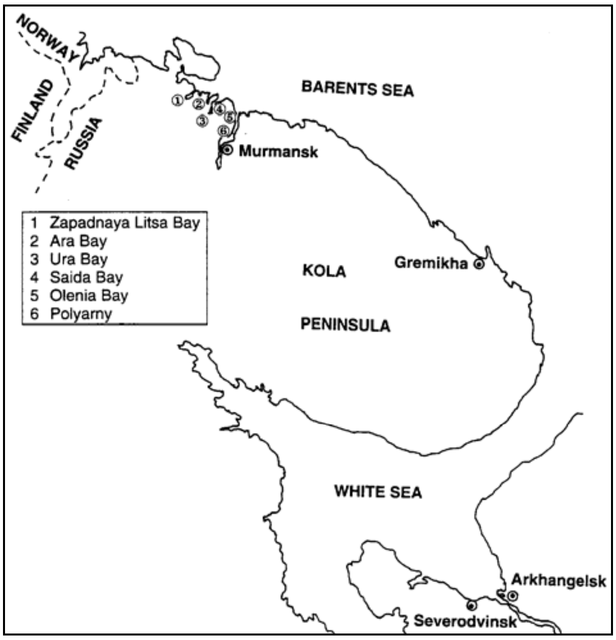

Figure 2.3. Map of the Kola Peninsula and adjacent areas showing the locations of non-defuelled, decommissioned nuclear submarines (cf. Table 2.4).

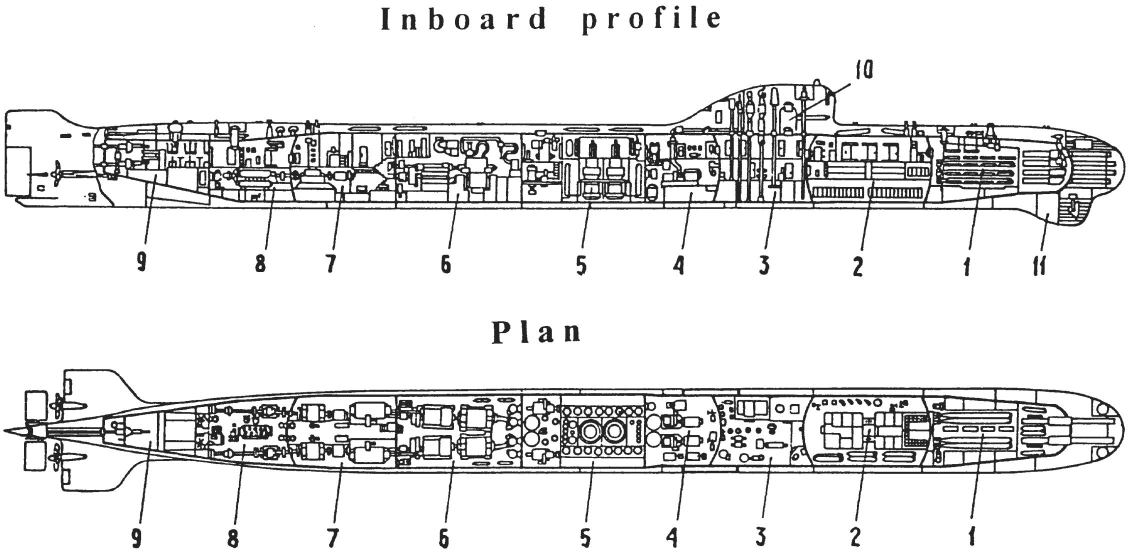

Figure 2.4. Sketch of Russia's first nuclear submarine, the Project 627/November class Leninskiy Komsomol *(*K-3*). The features indicated are (1) torpedo compartment, (2) accumulator battery compartment, (3) central control post, (4) diesel compartment, (5) reactor compartment, (6) main machinery compartment, (7) electric motors compartment, (8) accommodation compartment, (9) aft compartment, (10) conning tower and (11) sonar antenna.*

locations of those submarines listed earlier in Table 2.2. Russian plans in 1995 called for a total of 125 nuclear submarines to have been decommissioned by the year 2010 [Kværner, 1996]. The same plans estimate that the backlog of non-defuelled submarines at the Northern Fleet should steadily decrease and eventually reach zero by the year 2004, but this goal appears to require more support infrastructure than is presently available.

2.4.2 State of submarines

By now all nuclear submarines of the first generation have been withdrawn from service. This is true also for a significant number of the second generation nuclear submarines. As of 1997, approximately 85% of the withdrawn submarines had been withdrawn from service before 1993. The technical and procedural descriptions below refer mainly to [Khlopkin *et al.*, 1997].

2.4.2.1 First generation nuclear submarines

All of the first generation nuclear submarines (cf. Table 2.3) are of double-hull design, that is, they have a high-pressure inner hull and a light outer hull. The pressure hull of the nuclear submarine is divided into nine water-proof compartments by means of strong bulkheads (see Figure 2.4). The buoyancy reserve of about 20–35 % of the submerged displacement makes the nuclear submarine essentially unsinkable even when one of the compartments is flooded along with the adjoining main ballast tanks of port or starboard sides. The external surface of the outer hull is covered by a rubber cladding for acoustic protection.

The nuclear reactor plant of the submarine is located in the central compartment (the fifth when counting from the bow) of the pressure hull. The plant consists of two PWRs. High-

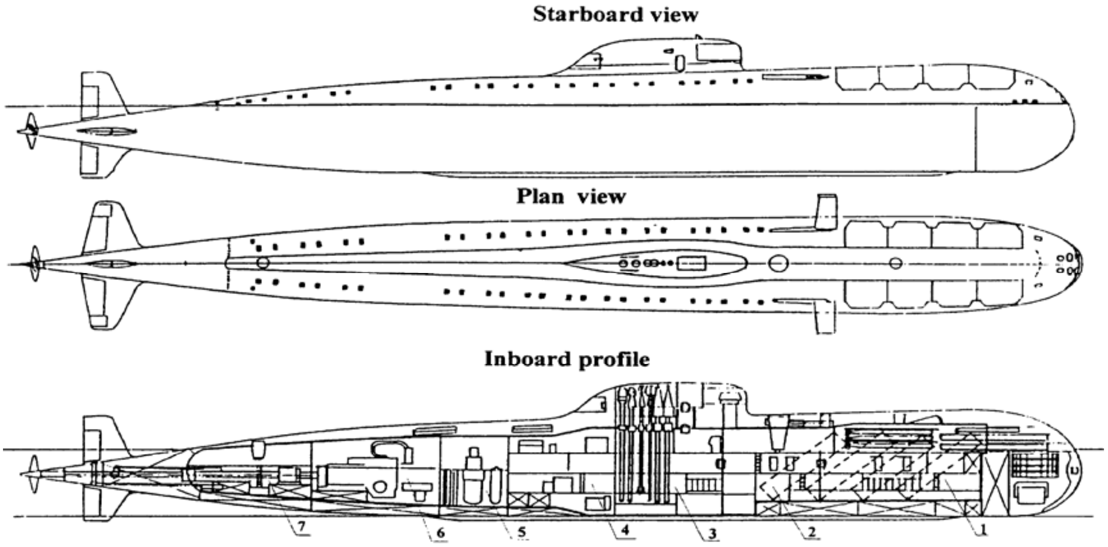

Figure 2.5. General view and inboard profile of a second generation nuclear submarine of Project 670M/Charlie-II class. It contains one PWR reactor capable of producing 90 MW_t. The numbers indicate (1) torpedo compartment, (2) accommodations and battery compartment, (3) central control post, (4) auxiliary equipment compartment, (5) reactor compartment, (6) main machinery compartment and (7) propulsion plant auxiliary equipment compartment.

purity distilled water is used both as coolant and as moderator. The thermal power of each reactor is 70 MW_t. The reactors are positioned in the middle of the submarine, one behind the other, in an airtight and waterproof enclosure inside the reactor compartment. This enclosure also contains primary circuit piping as well as circulation pumps, steam generators, coolant purification filters, heat exchangers and other components of the reactor plant auxiliary systems. The reactor has no connecting pipes below the upper edge of its nuclear core. Reactors, steam generators, pumps and all equipment of the primary circuit are surrounded by “biological shielding,” which consists of water tanks and lead walls. The purpose of the biological shielding is to protect the crew from ionising radiation that escapes the reactor vessel itself.

For supply of electricity, the nuclear submarine has:
- two main electric generators;
- two diesel-powered electric generators (producing direct current);
- two groups of electric batteries.

Start-up and cool-down of the reactors are provided either by the batteries or the diesel generators. Both produce direct current (DC).

2.4.2.2 Second generation nuclear submarines

Submarines of the second generation (cf. Table 2.3) also have a double hull. An example of such a submarine is shown in Figure 2.5. The outer hull has an acoustic protection cover while the pressure hull has a rubber cladding for sound insulation. The nuclear propulsion plants of

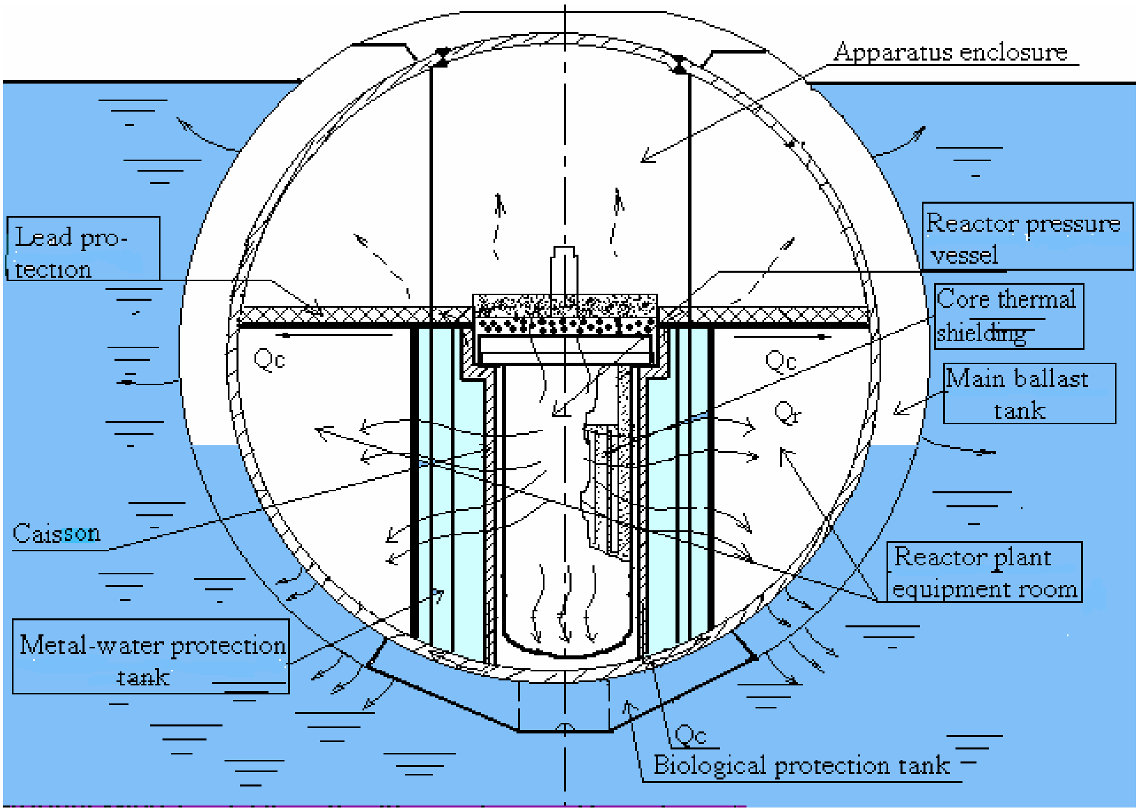

Figure 2.6. *A second generation reactor installation. Also included in the sketch are pathways for distribution of heat (Q_c indicate conduction and Q_r radiation). From [Khlopkin* et al.*, 1997].*

second generation submarines include one or two pressurised water reactors with a thermal power of either 72 MW_t or 90 MW_t and one or two main geared turbo units which directly rotate the corresponding propulsion shafts with propellers. Despite the difference in thermal power, second generation nuclear propulsion plants are all of the same design.

The steam-generating unit of a second generation propulsion plant consists of the nuclear reactor with its cylindrical thick-walled steel pressure vessel and of steam generators and primary circuit circulation pumps which are connected to manifolds on top of the reactor pressure vessel. The reactor core is located in the lower part of the reactor pressure vessel. This is mounted in a cylindrical steel caisson which is part of the biological shielding (see Figure 2.6). The reactor pressure vessel and its caisson lean on the pressure hull of the submarine. For additional biological protection, there is a water tank under the reactor.

Depending on their purpose, the second generation nuclear submarines contain different types of electric power supplies. Autonomous turbo generators of alternating current (AC) were used. The submarines also contain diesel generators and batteries as auxiliary power supplies.

2.4.2.3 Submarines with damaged cores

The Soviet Navy suffered a number of accidents with nuclear submarines in which the reactor cores were damaged such that the fuel assemblies could not be removed. In most cases, these accidents also resulted in contamination of the reactor compartment.

In the early years of the nuclear era, damaged reactor compartments were removed from their submarines and replaced by new reactor compartments. The damaged compartments were subsequently dumped into the sea east of Novaya Zemlya.

No non-defuelled naval reactors have been dumped since 1981. However, the Russian Navy still has a number of submarines with damaged cores, all resulting from accidents. Reportedly, at least two such accidents have occurred at the Northern Fleet and at least three at the Pacific Fleet.

The two submarines with damaged cores reportedly belonging to the Northern Fleet are believed to be *K-377* (Project 705/Alfa class), in which the liquid metal coolant solidified in 1972, and *K-131* (Project 675/Echo-II class), which suffered a loss-of-coolant accident in 1989. In the case of *K-377*, the reactor compartment and the two adjacent compartments have been cut out of the hull and sealed and are now being stored as a floating unit. Apparently no preparation for disposal has been made for *K-131*, but it is reported that air must be pumped into its hull in order to keep the submarine afloat.

The decommissioning of submarines with damaged cores represents a major problem. Removal of the damaged cores by cutting out and removing the fuel will require large resources and expose the workers to significant amounts of radiation. However, if nothing is done, sooner or later the damaged submarines will sink.

2.4.2.4 Submarines with liquid metal cooled reactors

Some Northern Fleet submarines (one Project 645/modified November class submarine that was sunk at Novaya Zemlya in 1981 and the seven Project 705/Alfa class submarines listed in Table 2.3) are equipped with liquid metal cooled reactors (LMRs). These reactors are cooled by a liquid lead-bismuth alloy and raise very specific safety concerns. Some of the general safety assumptions made in this report do not apply to LMRs; for instance, criticality accidents, reactor drainage and corrosion problems cannot be discussed in the same terms for both LMRs and PWRs. Furthermore, the decommissioning of LMRs raises the question of coolant disposal, since the coolant is radioactive.

Owing to a lack of relevant data, the particular problems presented by LMRs are not addressed further in this case study.

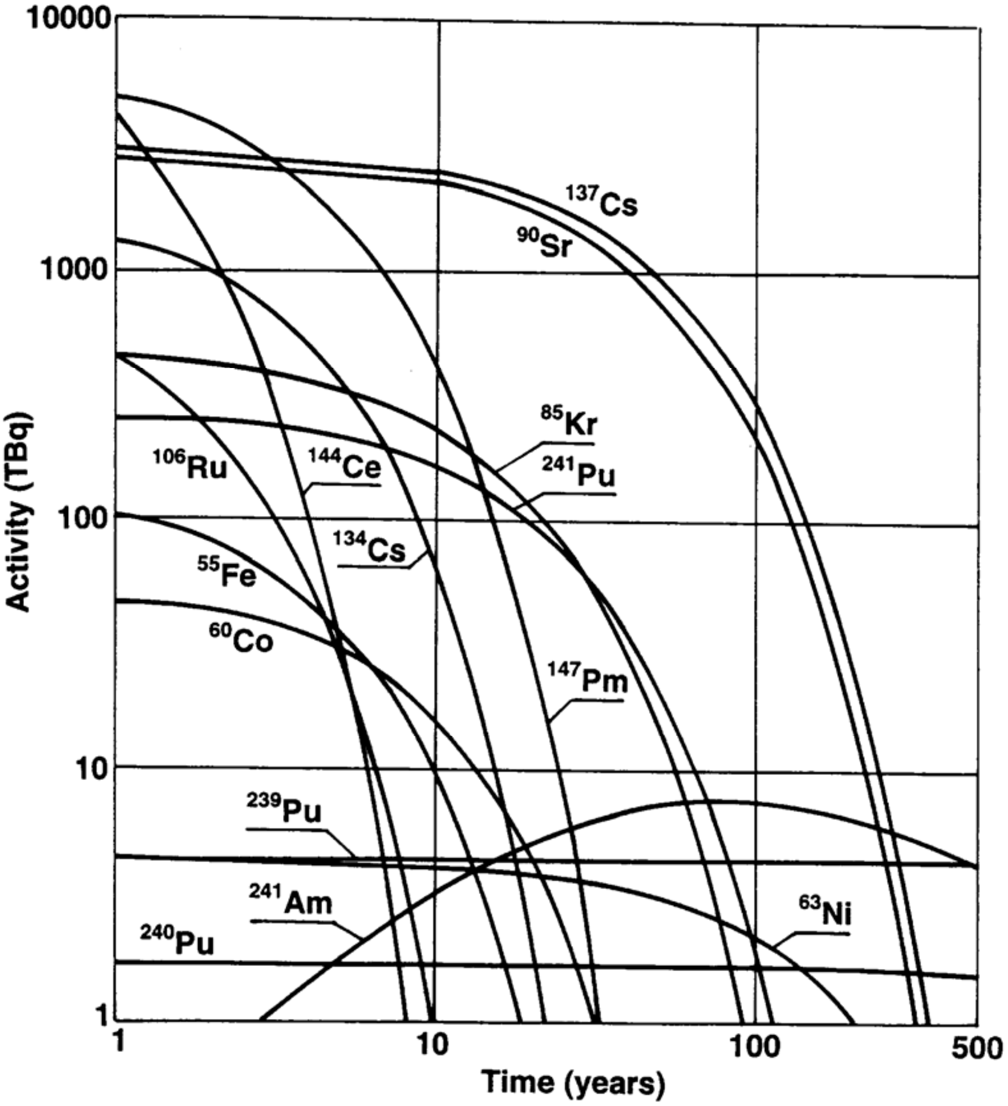

Figure 2.7. Contents of the most important radionuclides in the reactor of the sunken submarine Komsomolets *(*K-278*) as a function of time. The radioactivity of the long-lived fission products corresponds to permanent operation of the reactor for a period of five years. Based on [Khlopkin* et al.*, 1994] and reproduced from [Høibråten* et al.*, 1997].*

2.4.3 Nuclear inventory

Knowing the inventory of radionuclides in a given reactor core (especially during operation or shortly after shut-down), a fair amount of information about that particular reactor core may be deduced. For this reason, much information about nuclear inventories is classified and thus inaccessible.

However, some reactor information has been made publicly available in recent years with respect to the nuclear icebreaker/cargo ship *Sevmorput* [Register of Shipping of the USSR], the first reactors of the nuclear icebreaker *Lenin* [Sivintsev, 1993] and other dumped reactors [Sivintsev, 1994; Yefimov, 1994], as well as the sunken Project 685/Mike class submarine *Komsomolets* [NATO, 1995a]. As an example, Figure 2.7 shows the most important

Table 2.5. Inventory estimates of the most important radionuclides in the Sevmorput *reactor. Before shut-down, the reactor is assumed to have been operating at 50% power (that is, 67.5 MW_t) for 1.25 years. Five years after shut-down, the reactor is assumed to undergo a criticality accident involving 10^{20} fissions. A more extensive inventory is provided in Appendix A.*

Nuclide	Inventory (TBq)					
	Time after shut-down			Time after accident		
	0	1 year	5 years	0	1 hour	1 day
^{85}Kr	440	410	320	320	320	320
^{90}Sr	3800	3700	3400	3400	3400	3400
^{90}Y	3900	3700	3400	3400	3400	3400
^{106}Ru	5100	2600	170	170	170	170
^{106}Rh	5600	2600	170	170	170	170
^{131}I	62000	27	0.00	0.01	2.4	4.3
^{134}Cs	1600	1100	300	300	300	300
^{137}Cs	3800	3700	3400	3400	3400	3400
^{137m}Ba	3600	3500	3200	3200	3200	3200
^{144}Ce	79000	32000	930	930	930	930
^{144}Pr	79000	32000	930	930	930	930
^{147}Pm	11000	8900	3100	3100	3100	3100
^{237}U	16000	0.00	0.00	1.6	1.6	1.4
^{238}Np	1700	0.00	0.00	0.54	0.53	0.39
^{239}Np	33000	0.00	0.00	0.24	7.3	6.7
^{238}Pu	4.8	4.9	4.8	4.8	4.8	4.8
^{239}Pu	0.69	0.70	0.70	0.70	0.70	0.70
^{240}Pu	0.39	0.39	0.39	0.39	0.39	0.39
^{241}Pu	65	61	51	51	51	51
^{241}Am	0.03	0.13	0.49	0.49	0.49	0.49

radionuclides in the *Komsomolets* reactor as a function of time after the sinking. Note that there are PBq quantities of ^{137}Cs and ^{90}Sr even after 30–40 years.

Detailed estimates of the radionuclide inventory for the *Sevmorput* reactor have been made for this study. The results for a few of the most important radionuclides are shown in Table 2.5, while a much more comprehensive list is provided in Appendix A. In a hypothetical accident scenario, the reactor is assumed to undergo a criticality accident involving 10^{20} fissions five years after shut-down. As indicated by Table 2.5, such an accident does not much alter the long-term picture, but a closer examination of the data in Appendix A reveals that large quantities of short-lived radionuclides are generated in the accident.

2.4.4 Safety measures

The procedure of retiring a nuclear submarine from active service takes a long time, for a number of technical measures must be performed. In general, the time between reactor shut-down and formal withdrawal of the nuclear submarine from service (decommissioning) is more than one year (typically from one to three years). The measures performed during this period include the removal of different weaponry from the submarine, the dismantling and removal of equipment and systems which may be used either as spare parts for other submarines or are applicable for industrial use, the removal of materials that constitute fire or explosion hazards and the fulfilment of various additional safety measures, as well as ensuring the safe operation of equipment and systems necessary for floating storage of the submarine. Lubricants, air regeneration cartridges, electric batteries and instruments containing mercury are all removed from the submarine. (Most of the information here and in the remaining part of this section is from [Khlopkin *et al.*, 1997].)

At the time when a nuclear submarine is formally decommissioned, the reactors of its propulsion plant are completely cooled down, and the coolant temperature in the primary circuit does not exceed 100 °C. At this time, it is normally no longer necessary to actively pump the coolant. Residual heat produced in the reactor core (the *decay heat*) is transported to the sea by convection of both water and air, as well as heat radiation and heat conduction processes. For emergencies, electricity may be supplied from shore facilities. There is a diesel generator available on board the nuclear submarine, but because of the difficulty of providing sufficient maintenance, the Northern Fleet has chosen to supply decommissioned submarines with electric power from shore-based facilities only [Khlopkin *et al.*, 1997].

Special concerns arise if a decommissioned nuclear submarine is completely frozen in by sea ice. This affects not only the general safety of the ship, but also complicates the transfer of heat to the sea. The sea does not freeze at the mooring sites on the Kola Peninsula, but formation of ice is possible around Severodvinsk on the White Sea (cf. Figure 2.3). Here, special measures are taken to control and prevent ice formation around moored submarines and reactor compartments in floating storage.

Standard equipment for fire-fighting is available on board, and preparations have been made for possible replenishments from centralised shore-based facilities. Systems and equipment designated for preventing the sinking of the nuclear submarine are also in place. High-pressure air for the blowing of the main ballast tanks is kept in standard high-pressure balloons which are replenished if necessary from a compressor on board. The pressure in the primary circuit is kept at 1–1.5 MPa (that is, 10–15 atmospheres) in order to more easily discover leaks in this circuit.

A special commission checks a number of safety issues such as the radiation levels, the contamination of rooms and equipment, the application of corrosion protection measures for equipment and submarine hulls and the state of the main ballast tanks. The preparation of a nuclear submarine for long-term storage afloat is undertaken by a specially assigned acceptance commission, and when ready for storage, the vessel is certified by a special act.

2.4.4.1 Provisions for nuclear safety

In general, the nuclear cores on board decommissioned submarines have been in the reactors for a long time, and their removal requires certain precautionary measures. The water in the primary circuits receives special additives in order to decrease the corrosion rate of the various metals. The temperature of the coolant is kept above 5 °C to prevent it from freezing. Initially, the necessary heat is provided by the decay heat. Later, the reactor compartment must be heated. Keeping the primary circuit at a low temperature further inhibits corrosion.

The electric drives of all control rods and pumps are routinely disconnected from their power supplies by cutting out approximately 1-m long pieces of their power-supply cables. The ends of the remaining cables are insulated electrically.

The gears of the control rod drives (for scram rods, shim rods and other control rods) are completely disabled by means of welding and stoppers when each of the rods is in contact with its lower restrictive stop, that is, when it is fully inserted. The main control panel of the nuclear propulsion plant of the submarine is also disconnected from its power supply, and the reactor control room is locked and sealed (there is sufficient monitoring instrumentation in the reactor compartment outside the main control room).

The reactor compartment is periodically checked by personnel on duty. The presence of water in the primary circuits, as well as water pressure and temperature, are also checked. The total crew of a decommissioned submarine constitutes about 40% of the full crew of an operational submarine. There is always (around the clock) at least one person on duty aboard any moored, decommissioned nuclear submarine.

With the passage of time, the heat released from nuclear decay decreases, and eventually (three years or more after reactor shut-down) complete removal of the coolant from the primary circuit is possible. This procedure, presently only at the experimental stage, would simplify supervision of the reactor compartment, as the temperature would no longer have to be controlled. Removal of the coolant after several years of storage would not result in a significant increase of the temperature of the fuel rods. It is therefore believed that oxidation or nitridation of the fuel cladding as a consequence of its exposure to the air will not constitute a problem. The low corrosion rate of the stainless steel cladding should permit dry storage of spent fuel inside the reactor for a long time.

The Flag Officer of the Naval Staff Mechanical Engineering Service is responsible for quality assurance of the safety measures listed above. The same service carries out periodical inspections of the technical state of the nuclear submarine throughout its long period of storage afloat.

2.4.5 Defuelling

The defuelling of submarine reactors is considered to be potentially dangerous work. If the control rods are removed, the nuclear core can go strongly supercritical even after complete burn-up. Special technical and organisational measures are therefore implemented in order to prevent criticality accidents during the defuelling process. Defuelling operations are carried out by specially trained and certified personnel under strict auspices of the Naval Base Physical Laboratory. The ensuing description of the defuelling process is based on [Khlopkin *et al.*, 1997].

The most effective technical measure for preventing criticality accidents during the defuelling of a nuclear submarine is the removal of water from the reactor vessels and the primary circuits. This removal of the neutron moderator puts the nuclear core into a deeply subcritical state; it will remain subcritical even if all neutron absorbers are removed. After drainage has taken place, the absence of water in the primary circuits is thoroughly verified. One of the scram rods is removed along with its casing, and a special suction tube and a feeler are inserted into the hole. Full drainage of water from the secondary and tertiary circuits, drainage tanks, and so forth are also verified. All pipelines connecting these systems to the primary circuit are dismantled. All possible entries of water into the reactor are completely sealed off, and this blanking is carefully tested. As of 1997, drainage of primary circuits had only taken place immediately prior to the defuelling of the reactor, and all drained reactors had been shut down for at least three years.

The removal of the massive reactor pressure vessel lid is one of the most complicated technical operations in the defuelling process. After being tightly attached to the reactor vessel for so long, the lid cannot simply be lifted straight up by a crane. To initiate the lifting, jacks are now used (referred to as “tearing off” the lid); earlier, pressure build-up inside the reactor vessel was used for the same purpose (“firing” the lid). In preparation for tearing off the lid, all nuts of its fastening studs are first loosened by 50–100 mm. Then the lid is torn off from its seals and carefully moved up to this maximum height. Only at this point are all the nuts removed, and the lid is very slowly lifted up by a special crane (which is located on board a service ship usually referred to as a *floating technical base*) to a height of about 1.5 m. The lifting takes place under strict visual monitoring of the positions of all important parts such as scram rods and control rods.

The defuelling itself is performed by means of a *refuelling machine*. The machine is mounted on top of the reactor where it replaces the pressure vessel lid as shown in Figure 2.8. With the help of the refuelling machine’s positioning device, a refuelling transfer container is positioned above the fuel assembly to be extracted. Using a manually controlled winch, an operator lowers expansion tongs inside the container and clamps the specially configured head of the selected fuel assembly. This operation can be visually monitored through a periscope. The fuel assembly is then pulled up into the transfer container by the winch, and the bottom of the container is locked by a shielding damper. The crane brings the container with the spent fuel assembly to the floating technical base and lowers it into a storage pool in the ship’s hold. In the storage pool there are special casings into which the spent fuel assemblies are placed. Each casing can hold seven fuel assemblies. After being filled with fuel assemblies, the casing is sealed. Complete defuelling of one reactor is accomplished in about three days. The sealed

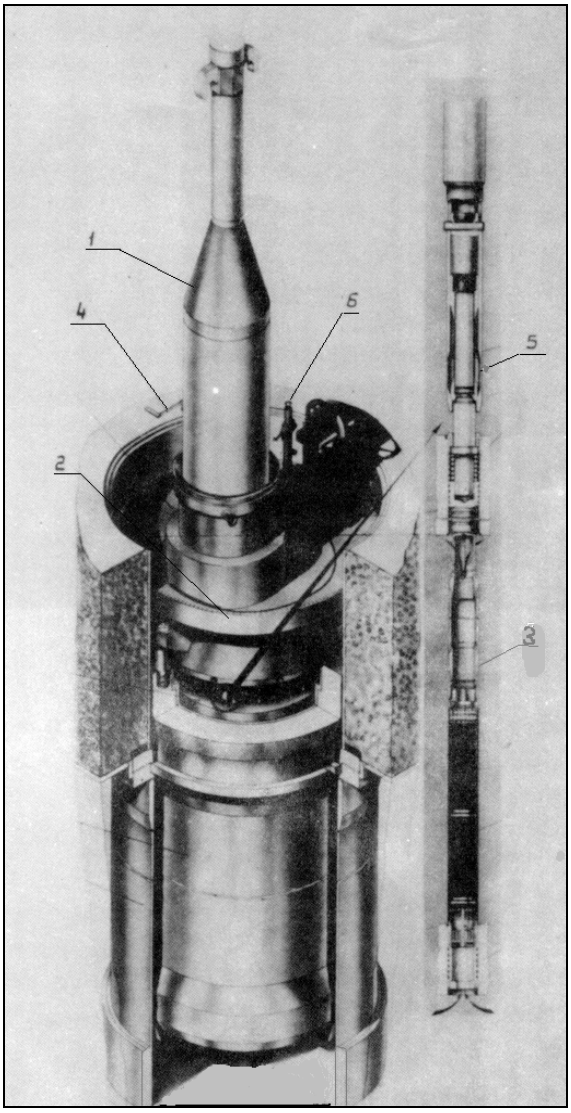

Figure 2.8. Operation of the refuelling machine. The numbered features are (1) refuelling container, (2) coordinate-positioning device, (3) spent fuel assembly, (4) protective shielding, (5) expansion tongs and (6) periscope.

casings with spent nuclear fuel can then be placed into transport containers for transport to a reprocessing plant or an on-land storage facility (water-pool type or dry; the latter is preferable).

Before being drained, the water in the primary circuit provided additional radiation shielding. The radiation level above the reactor lid therefore increases following drainage. However, the refuelling machine significantly attenuates the flux of gamma radiation, and the collective dose for personnel per defuelling operation is typically about 0.03–0.04 manSv.

2.5 The International Arctic Seas Assessment Project (IASAP)

To obtain additional perspectives on risks due to sunken nuclear submarines and dumped nuclear waste and spent nuclear fuel, it is worth examining a number of reactors which were intentionally dumped in Arctic waters.

During the 1960s and 1970s, the former Soviet Union disposed of several reactors that had suffered damage during their operating life in the Kara Sea. In 1992, the rest of the world became aware of this, along with the fact that other low-level and intermediate-level solid and liquid wastes had also been disposed of in the Barents Sea and the Kara Sea. The IAEA proposed a study of the related health risks and environmental hazards, the International Arctic Seas Assessment Project (IASAP). This proposal was supported at the Fifteenth Consultative Meeting of the Contracting Parties to the “Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter” (The London Convention of 1972).

The project began in 1993. Working groups were established to survey the current radiological situation in these Arctic waters, to examine the radionuclide inventories of the dumped objects and their containment, to model the environmental transport of the released radionuclides and to assess their radiological impact on man. Finally, the IASAP would examine the feasibility, costs and benefits of possible remedial action.

The “White Book” [Yablokov *et al.*, 1993] listed total inventories for all the categories. Since the activity contained in the reactors made up the largest component of the waste (4.7 PBq in 1994), the study concentrated on the six reactors that were dumped with spent nuclear fuel, the ten reactors without fuel, and a special steel box containing damaged fuel from the nuclear icebreaker *Lenin*. Two of the six fuelled reactors were of LMR type; these reactors were dumped in their original submarine. The other reactors, first generation PWRs, were cut out of their submarines and dumped in their original reactor compartments.

Briefly summarising the results of the study, the IASAP *Environmental Survey Group* found limited evidence for contamination of the Kara Sea that could be attributed to the dumped objects.

The *Source Term Group*, with help from its Russian members, was able to establish firstly the likely inventories of the dumped fuel and the activity in the steels of the reactor components. Secondly, information about the containment barriers that had been put in place at the time of dumping was obtained. With this data, a model to predict the release rates for all the radioisotopes into the Kara Sea was developed, based on release by corrosion from the materials. Figure 2.9 shows the total predicted release rate from all the fuelled and defuelled PWR reactors into the Kara Sea. The LMRs are excluded from this graph, as the release rate from these reactors is very slow and insignificant by comparison.

Possible criticality of the dumped reactors was considered and shown to be unlikely for the PWRs. For the dumped submarine with two fuelled LMRs, criticality was a possibility, but even if this were to happen, it would be hundreds of years into the future [Warden *et al.*, 1997].

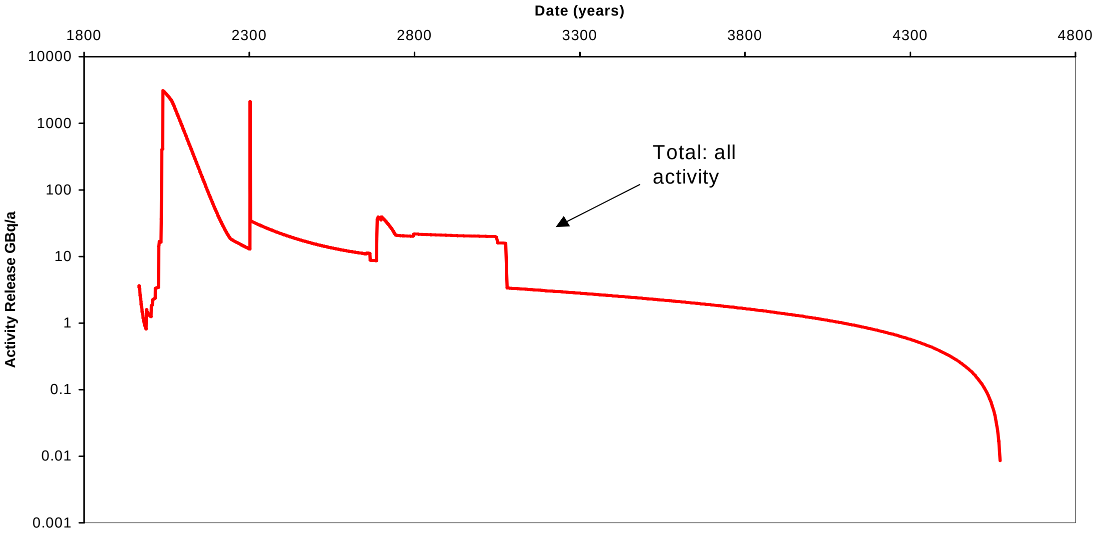

Figure 2.9. Predicted release rate of all radionuclides from the pressurised water reactors dumped in the Kara Sea [IAEA, 1997a].

The *Modelling and Assessment Group* of the IASAP took the release rate data and built local and world ocean circulation models to transport and disperse the radionuclides. Local target populations were predicted to receive the maximum annual doses, but these were generally shown to be lower than 0.1 μSv per year. (As a comparison, inhabitants of Northern Russia consume some 100 μSv per year from seafood containing naturally occurring ^{210}Po.) The world collective dose over the next 1000 years from the ^{14}C content of the inventory was shown to be about 8 manSv. This is three orders of magnitude lower than the collective dose from the same naturally occurring ^{210}Po.

The exception to the above target populations was a group of military personnel patrolling the foreshores of the fjords of Novaya Zemlya where the reactors were dumped. Their annual dose may reach 700 μSv, which is comparable to the natural background doses.

The *Remedial Actions Group* considered a number of options for remediation. Confining the study to the box containing damaged fuel from the *Lenin*, the group showed from a cost/benefit analysis that recovery of the fuel was not warranted. The whole study concluded that except for local areas of Novaya Zemlya, there would be little hazard from the dumped reactors, providing the sites were monitored and controlled, but left undisturbed.

The IASAP reported to the London Convention in 1997 [IAEA, 1997b]. The work of the Environmental Study Group and of the Source Term Group has been published [Strand *et al.*, 1997; IAEA, 1997a]. As of early 1998, the IAEA has yet to print the work of the Modelling and Assessment Group [IAEA, 1997c] and the Remedial Actions Group, but the conclusions of the modelling study have been reported [Scott *et al.*, 1997].

A separate study has been initiated under the auspices of the European Commission to investigate the same problem [Ali *et al.*, 1997a; Ali *et al.*, 1997b].

3 ACCIDENT ANALYSIS BASIS

This chapter provides the basis for the more comprehensive accident analyses that will be carried out in Chapter 4. First, models of reactor plants are developed. Then various accident scenarios are discussed, and those scenarios that are considered to imply the highest risks are selected for further analysis in Chapter 4.

3.1 Submarine analysis models

Russian nuclear submarines are customarily divided into four generations. The first two generations are listed in Table 2.4. Construction of the third generation submarines covers the period from 1977 to the present and includes the following classes of vessels:
Project 941/Typhoon, Project 949/Oscar-I, Project 949A/Oscar-II, Project 945 and 945A/Sierra and Project 971/Akula. Construction of the fourth generation of submarines began in 1993 with the *Severodvinsk* of the Project 885/Granay class. *Severodvinsk* was launched in 1995, but has not yet been commissioned.

As mentioned earlier, by now all first generation submarines, as well as a number of second generation submarines, have been decommissioned. Since there are no submarines of later generations in a non-defuelled, decommissioned state, the discussion below is limited to first and second generation vessels only.

3.1.1 Design features

Design information is available on two merchant ships: the nuclear icebreaker *Lenin*, which was constructed in the late 1950s and commissioned in 1959, and the icebreaker/cargo ship *Sevmorput*, which was constructed between 1984 and 1988. Changes were made to the reactor plant of the *Lenin* in the late 1960s after reactor damage occurred in 1965 to one of its three original reactors. The *Lenin* is now decommissioned and is moored at the nuclear icebreaker base Atomflot near Murmansk.

The first *Lenin* propulsion plant (OK-150), which is believed to be representative of those installed in the first generation submarines, had three reactors, each with a power of 90 MW_t [Sivintsev, 1993]. The second propulsion plant had two reactors; hence the power of each must have been upgraded to about 135 MW_t. No information is given in [Sivintsev, 1993] on the second *Lenin* propulsion plant. The *Sevmorput* propulsion plant has one reactor with a power of 135 MW_t [Register of Shipping of the USSR]. It is generally believed that the propulsion plant of second generation submarines would be similar to that of the second *Lenin* plant, which in turn appears to be similar in size to that of the *Sevmorput* plant.

During the Pilot Study, further information on decommissioned submarines became available through a Russian study [Khlopkin *et al.*, 1997]. For details, see Section 2.4.

Table 3.1. Published key parameters for a number of first generation and second generation submarines. The information has been assembled mainly from [Pavlov, 1997] and [Nilsen et al.*, 1996].*

Project/ class	Type	Displacement (tonnes)	Speed (knots)	Reactor type	No. of reactors	Power (MW$_t$)	Shaft power (hp)
Submarines of the first generation							
627/November	SSN	4750	30	OK-150/VM-A	2	70	35000
658/Hotel	SSBN	5000	26	OK-150/VM-A	2	70	35000
659/Echo-I	SSGN	5000	29	OK-150/VM-A	2	70	30000
675/Echo-II	SSGN	6000	29	OK-150/VM-A	2	70	35000
Submarines of the second generation							
667/Yankee	SSBN	9300	26	OK-700/VM-4	2	90	40000
667B/Delta-I	SSBN	10000	26	OK-700/VM-4	2	90	40000
667BD/Delta-II	SSBN	10500	25	OK-700/VM-4	2	90	40000
667BDR/Delta-III	SSBN	10600	25	OK-700/VM-4	2	90	60000
667BDRM/Delta-IV	SSBN	11700	24	OK-700/VM-4	2	90	60000
670A/Charlie-I	SSGN	5500	26	OK-350/VM-4	1	90	18000
670M/Charlie-II	SSGN	5500	26	OK-350/VM-4	1	90	18000
671/Victor-I	SSN	5100	32	OK-300/VM-4	2	72	31000
671PT/Victor-II	SSN	5900	32	OK-300/VM-4	2	72	31000
671PTM/Victor-III	SSN	6000	32	OK-300/VM-4	2	72	31000

3.1.2 Reactor power

Table 3.1 lists the available public information on a number of Russian submarines. From this table it appears that all first generation submarines were powered by the same reactor plant and a VM-A reactor core. All first generation submarines (SSNs, SSBNs and SSGNs) had two power plants. Normally, the published data on submarine speed and shaft horsepower are understated as such data are classified.

According to [Sivintsev, 1993], the first *Lenin* reactors had a power of 90 MW$_t$ each; hence it is not unreasonable to assume that the VM-A reactor core that powered all first generation submarines also had a power of 90 MW$_t$. Note that the Project 670/Charlie and the Project 659 and 675/Echo class submarines have a similar size hull, while the Project 670/Charlie class submarine has only one reactor. If the Project 659 and 675/Echo class vessels each have two reactors of 90 MW$_t$, then the Project 670/Charlie class submarines having only one reactor each, would have to have a reactor power of about 180 MW$_t$ (unless the operational characteristics were significantly different). Note also that both the second *Lenin* reactors and the *Sevmorput* had a reactor power of 135 MW$_t$, and these reactors are believed to be more representative of those found in second generation submarines. Since the true reactor powers are unknown, for the purposes of this study a reactor power of 90 MW$_t$ is assumed to be representative for all first generation submarines and a reactor power of 180 MW$_t$ for all second generation submarines. Since power is an important parameter in assessing environmental effects, it is prudent to be conservative.

3.1.3 First generation submarines

The reactor plant for first generation submarines (SSNs, SSBNs and SSGNs) is assumed to be very similar to that originally used on the nuclear icebreaker *Lenin* (except that only the *Lenin* reactors had pipes connected to the reactor vessel at a level below the top of the nuclear core). Accordingly, the reactor model below is based on publicly available design information for the *Lenin*.

3.1.3.1 Reactor plant model

The reactor plant for first generation submarines is assumed to have two cooling loops. Each loop has one pump and one steam generator and can be completely isolated from the reactor vessel by two isolation valves. This type of plant layout is known as a *distributed plant*, for the key reactor cooling equipment is distributed throughout the reactor compartment and connected by long lengths of piping.

3.1.3.2 Reactor core model

The reactor model used in this study has the following design features or characteristics:

Thermal power	90 $\mathrm{MW_t}$
Reactor core diameter	1 m
Reactor core active height	1.6 m
Fuel power density	76 $\mathrm{MW_t/m^3}$
In-vessel shielding	three concentric layers of steel separated by water, a beryllium reflector and the core barrel
Reactor vessel diameter	1.5 m inner/1.9 m outer
Reactor vessel height	3.5 m (inner)
Number of control rods	30
Number of fuel assemblies	213
Fuel assembly tube diameter	54.5 mm outer/52.5 mm inner
Number of fuel pins per fuel assembly	36
Fuel pin diameter	6.1 mm outer/4.6 mm inner
Fuel pellet material	UO_2 with 5% enrichment
UO_2 quantity per assembly	8 kg
Total UO_2 in core	1704 kg (80 kg ^{235}U)
Inlet coolant temperature	260 °C
Outlet coolant temperature	312 °C
Cooling water flow rate	130 kg/s
Coolant pressure	18 MPa (20 MPa design)

The fuel pin arrangement inside each fuel assembly is shown in Figure 3.1, and the fuel assembly arrangement inside the reactor vessel is shown in Figure 3.2.

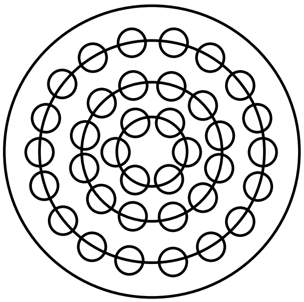

Figure 3.1. Assumed fuel assembly cross-section (36-pin fuel bundle) for first generation submarines.

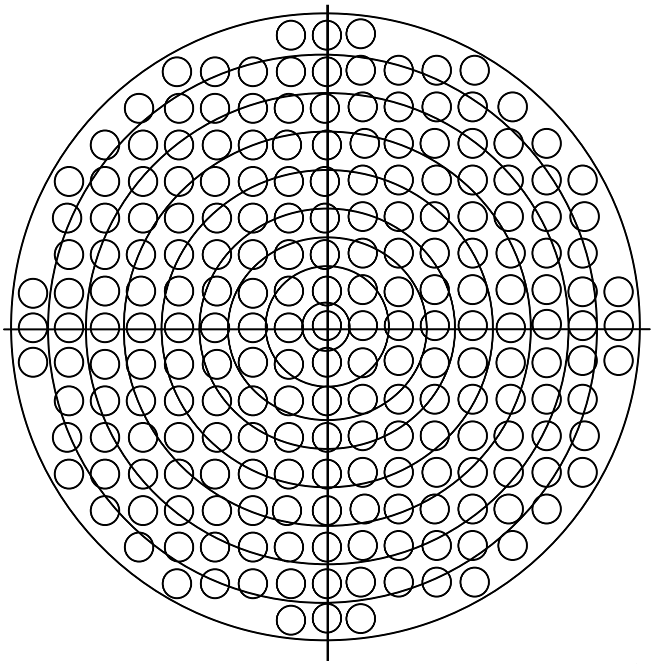

Figure 3.2. First generation reactor cross-section (213 fuel assemblies).

3.1.4 Second generation submarines

The reactor plant for second generation submarines is assumed to be similar to that used in the *Sevmorput* (KLT-40 design), but with longer cooling pipes connecting the pumps and steam generators to the reactor vessel. As discussed in Section 3.1.2, the reactor power is assumed to be 180 MW_t for all second generation submarines (SSNs, SSBNs and SSGNs). The *Sevmorput* reactor power was 135 MW_t; hence, where appropriate, parameters are scaled on the basis of reactor power.

3.1.4.1 Reactor plant model

The reactor plant for second generation submarines is assumed to have four cooling loops. Each loop has one pump and one steam generator. The primary coolant is in the shell side[3] of the steam generator, and feedwater is fed down from the top of the steam generator inside the

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[3] Heat exchange equipment generally consists of a vessel ("shell") with bundles of tubes inside. Inside the tubes is referred to as "tube side," while outside the tubes (but inside the shell) is "shell side."

feedwater tubes. These tubes feed the steam tubes at the bottom of the steam generator, and steam is discharged at the top.

The primary coolant pumps have “canned” motors which eliminate a potential leakage path for reactor coolant.

3.1.4.2 Reactor core model

The core designs of *Lenin* and *Sevmorput* differ with respect to four key parameters: quantity of ^{235}U, fuel composition, core power density and core aspect ratio. The amount of ^{235}U is 1.11 kg/MW_t for the *Sevmorput* core and 0.89 kg/MW_t for the *Lenin* core. This means that the *Sevmorput* reactor has a longer life in terms of MW-days of operation than the *Lenin* reactors had. The second generation reactor model has 0.94 kg of ^{235}U per MW_t of reactor power. This gives the second generation core a slightly longer life than the first generation core (about 10.3 years for an average operating power of 25% of full power). This compares with about 9.7 years for *Lenin* and about 12.2 years for *Sevmorput*.

Lenin used ceramic UO_2 fuel and *Sevmorput* has metal U-Zr fuel. Both have cylindrical fuel assemblies of approximately the same diameter. The model for second generation reactors assumes ceramic UO_2 fuel.

The power density for the *Lenin* reactor core is 76 MW/m^3 versus 117 MW/m^3 for *Sevmorput*. The higher power density is more representative of modern power-reactor designs. A value similar to that of the *Lenin* core is assumed for the second generation reactor model.

The aspect ratio (active height to diameter) of the *Lenin* reactor core is about 1.6, while that of the *Sevmorput* is about 0.8. The reduction in aspect ratio reflects an attempt by designers to reduce fuel damage from vibration and shock. The shorter fuel assemblies are more robust and can better withstand mechanical shocks and vibrations. An aspect ratio of about 1 (0.93) is assumed for the second generation reactor model.

The reactor model used in this study has the following design features or characteristics:

• Thermal power	180 MW_t
• Reactor core diameter	1.5 m
• Reactor core active height	1.4 m
• Fuel power density	73 MW_t/m^3
• In-vessel shielding	three concentric layers of steel separated by water, a beryllium reflector and the core barrel
• Reactor vessel diameter	2.0 m inner/2.4 m outer
• Reactor vessel height	3.5 m (inner)
• Number of control rods	60
• Number of fuel assemblies	493
• Fuel assembly tube diameter	54.5 mm outer/52.5 mm inner

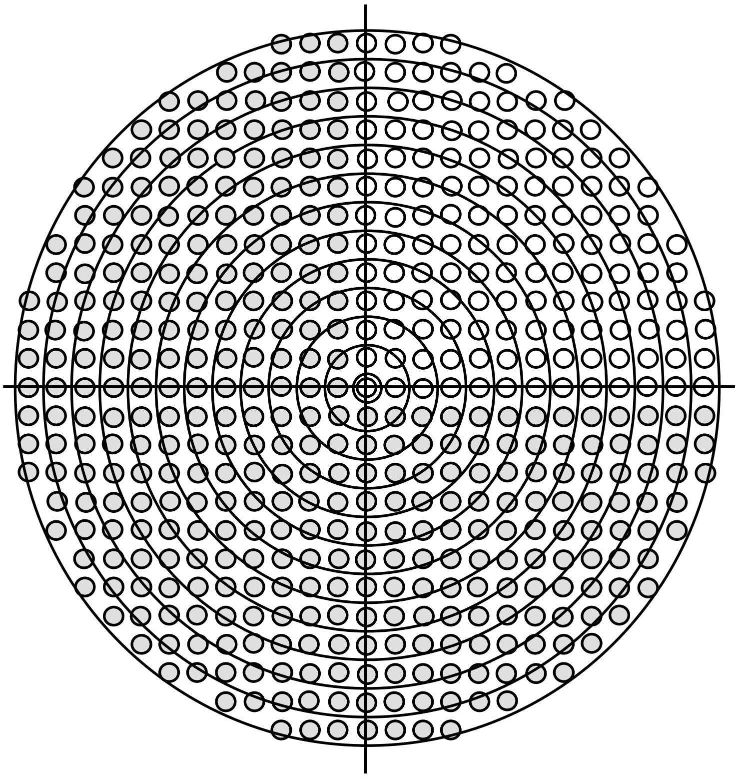

Figure 3.3. Second generation reactor core cross-section (493 fuel assemblies).

• Number of fuel pins per fuel assembly	36
• Fuel pin diameter	6.1 mm outer/4.6 mm inner
• Fuel pellet material	UO_2 with 5% enrichment
• UO_2 quantity per assembly	7 kg
• Total UO_2 in core	3600 kg (169 kg ^{235}U)
• Inlet coolant temperature	260 °C
• Outlet coolant temperature	312 °C
• Cooling water flow rate	260 kg/s

In the second generation model, the fuel assembly design is the same as that for the first generation model (see Figure 3.1). The arrangement of fuel assemblies inside the reactor vessel is shown in Figure 3.3. The simplified ring model used in the analysis is shown in Figure 3.4. The power distribution in this simplified ring model follows a radial cosine distribution as shown in Table 3.2.

It has been argued that many of the decommissioned submarines use metallic fuel (U-Zr or maybe U-Al alloys) [Børresen *et al.*, 1998]. If so, this is unlikely to significantly alter the conclusions drawn in this report.

3.1.5 Decay power

As demonstrated by the extensive radionuclide inventory listed in Appendix A, once a model for the reactor core and its operating time has been established, the relative abundance of the

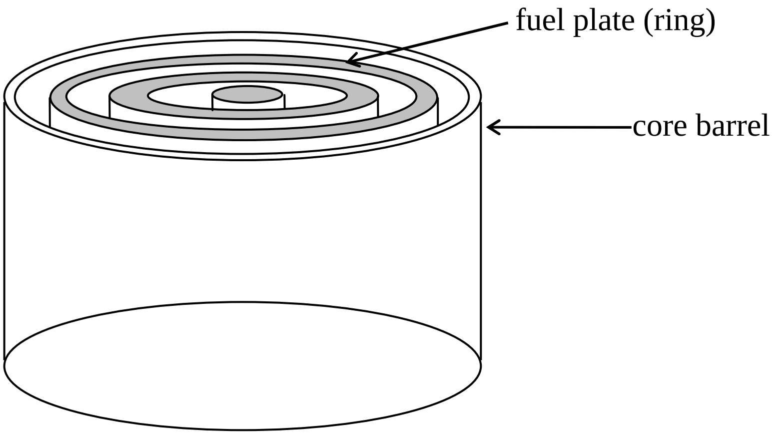

Figure 3.4. Simplified ring model of the reactor core. In the actual analysis, more rings are used than shown here (cf. Table 3.2).

Table 3.2. Power distribution in the simplified second generation core model.

Ring no.	No. of fuel assemblies per ring	Average assembly power (kW)	Total ring power (kW)
1	1	460	460
2	8	459	3670
3	14	455	6368
4	20	448	8970
5	26	440	11429
6	32	428	13703
7	38	414	15751
8	44	398	17531
9	50	380	19007
10	56	360	20145
11	62	337	20914
12	68	313	21285
13	74	287	21236
Total	493		180470

various radionuclides in the spent nuclear fuel may be calculated. It is also possible to estimate the *decay power* that must be removed from the core. This is the kinetic energy of the decay products, and it manifests itself macroscopically as heat.

Estimated decay power for first generation and second generation reactors are shown in Table 3.3 as a function of time from reactor shut-down. One may note that the decay power is about 7 kW and about 14 kW one year after shut-down for first generation and second generation reactors, respectively. Three years after shut-down, these values are reduced to a little over 2 kW and about 4.5 kW, respectively.

Table 3.3. Estimated decay power for first generation and second generation reactors. The calculations assume average reactor operation at 25% of full power.

Time since shutdown (years)	Decay power (kW)	
	First generation	Second generation
0.25	18.0	36.0
0.50	11.2	22.5
1.0	6.75	13.5
1.5	4.50	9.0
2.0	3.38	6.75
3.0	2.25	4.50
4.0	1.58	3.15
5.0	1.12	2.25

3.1.6 Moored, decommissioned submarines

The following information on laid-up submarines was obtained from [Khlopkin *et al.*, 1997] (see also Section 2.4):

- the decommissioning process does not start until at least one year after final reactor shutdown; hence, all laid-up submarines have a decay power which is less than 0.03% of the average power prior to reactor shutdown (about 25% of full power);

- the reactor coolant pressure is maintained in the range of 1–1.5 MPa and is checked at least once per day by the watch;

- the core decay power is removed by entirely passive means – no pumps are required at all during the lay-up period;

- decay power is transferred from the core to the sea by convection of both water and air and by conduction through the submarine hull;

- three years after final reactor shut-down, core decay power can be removed even with the pressure vessel empty (that is, drained of water);

- the gears of the control-rod drives are completely disabled by welding mechanical stops to them;

- the pumps and the electric drives of the control rods are deprived of electric power by the removal of a one-metre section of cable from the supply lines.

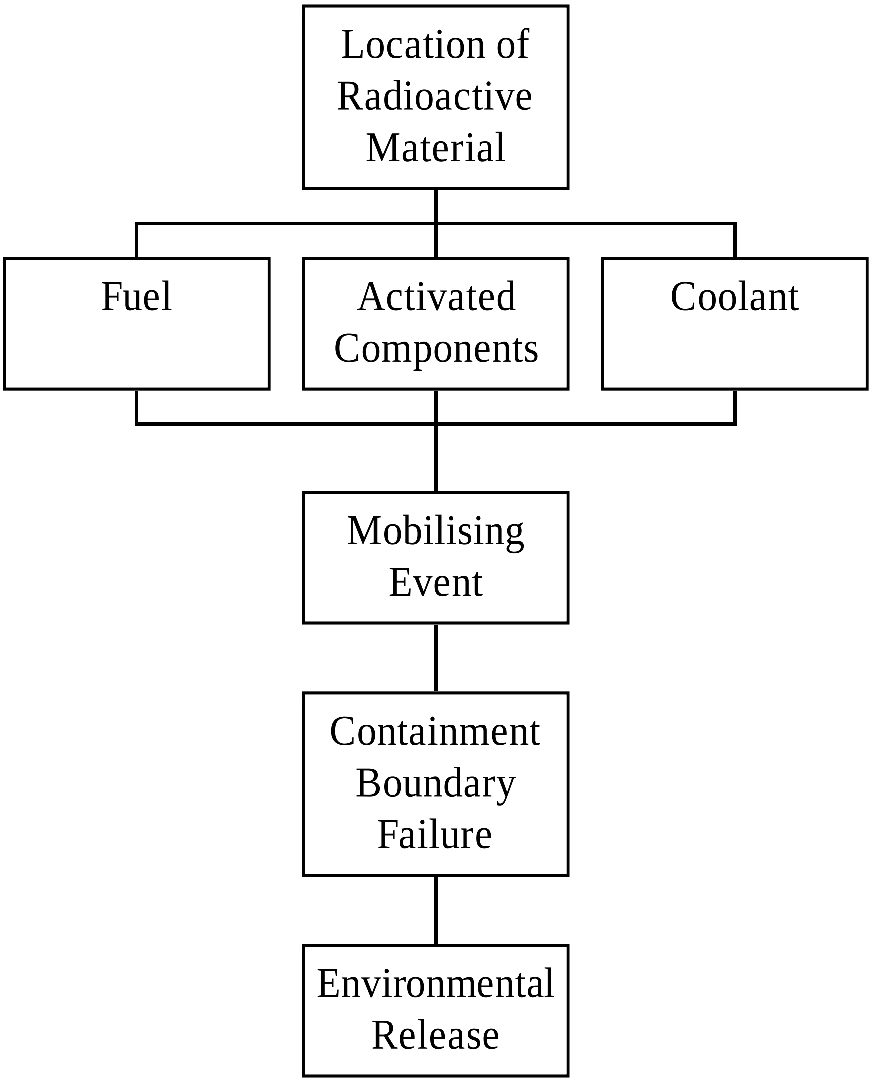

Figure 3.5. Logic diagram for an environmental release of radionuclides used in system review of the submarine model.

3.2 Systematic review of potential submarine accidents

A systematic review of the submarine model was performed to identify events that could lead to a release of radionuclides to the environment [Natalizio, 1997]. The key areas containing radioactive material are shown in the logic diagram in Figure 3.5. As indicated by the figure, two conditions must be present concurrently for an environmental release to occur:

- an event with sufficient energy to dislodge the radioactive material from its normal location; and
- a failure of the containment boundary (unless the mobilising event also has sufficient energy to breach the containment boundary directly).

The largest inventory of radioactive materials is found in the fuel. Furthermore, the fuel has sufficient thermal energy to cause the radioactive material to be mobilised and dispersed inside the reactor compartment. The amount of radioactivity in the fuel is on the order of 100 PBq

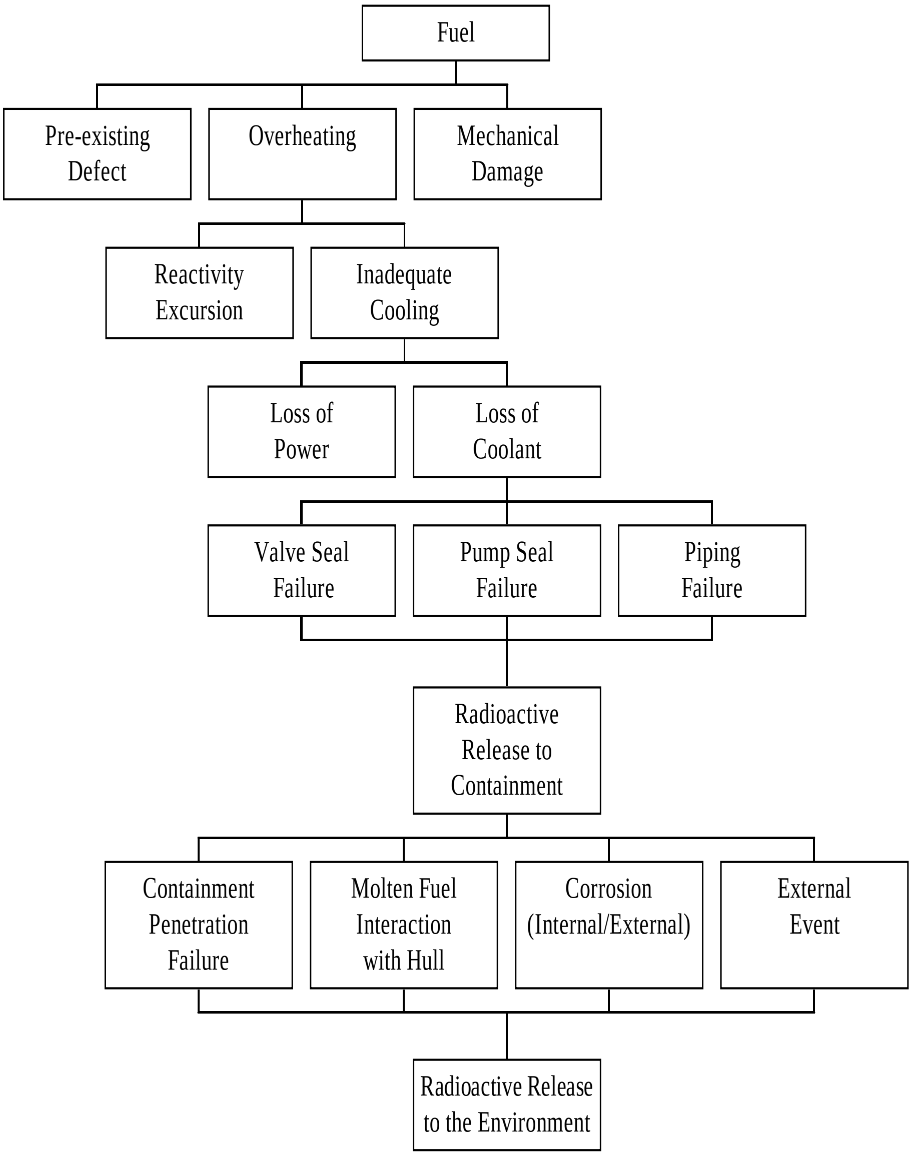

Figure 3.6. Illustrative example of logic diagram used for the systematic identification of initiating events.

(cf. Appendix A). By comparison, the reactor structures (mostly the pressure vessel and shield tank) contain on the order of 10 PBq of radionuclides. Also, the reactor structures do not have sufficient energy to cause mobilisation of the imbedded activation products (except for the electrochemical potential which can cause corrosion and dissolution of the activation products over very long time scales (decades)). The coolant contains less than 1 GBq of radioactivity which is not enough to constitute a cross-border environmental concern. It is assumed that the waste arising from the coolant purification system (purification filters and ion exchange resin) has been removed from the submarine in preparation for lay-up.

Figure 3.6 identifies in a systematic way some of the internal events that could cause radioactivity inside the fuel to be relocated. The figure is also illustrative of the process used for generating a comprehensive list of initiating events. The list is subsequently reviewed to identify those events that require further assessment.

Figure 3.6 identifies three possible mechanisms that could lead to the mobilisation of radioactivity from the fuel:

- existing defects in the fuel cladding that could allow volatile material to escape and water (reactor coolant) to come into contact with the fuel (and thereby leach radioactive material);
- mechanical damage from shock, for example, which could lead to leaching of radioactive material; and
- overheating.

Of the three, overheating is of most concern. The other two mechanisms have limited impact on the transport of radioactivity and operate on a longer time scale. Overheating can occur due to inadequate cooling of the fuel and/or a power excursion (also known as a criticality accident or a reactivity transient). The example provided in Figure 3.6 concerns inadequate cooling of the fuel. Heat removal from the reactor core can be degraded by loss of coolant circulation (caused, for example, by loss of electric power to the reactor pumps) or through loss of the coolant itself (which could occur due to a valve or pump seal failure or cracks in the pipes of the cooling system). As discussed in Section 3.1.6, electric power is not required for removing decay heat from the reactor core; therefore, leakage of the coolant is the only mechanism that could lead to fuel overheating.

Figure 3.6 also shows that once the radioactivity is displaced from the fuel to the reactor compartment, there must be a failure of the compartment boundary in order for any radioactive materials to enter the environment. Such failures could arise from external events (a collision between ships, for example), hull corrosion (either from internal or external mechanisms), cracks in the piping penetrating the reactor compartment or, in an extreme event, through the interaction of molten fuel with the submarine hull.

There is of course a wide spectrum of accidents that may occur in a nuclear-propelled submarine. Some may be initiated by events inside the submarine (such as equipment failure), while others may be initiated by events outside the submarine (such as a collision with another ship). The different types of accidents are systematically reviewed below.

3.2.1 Internal events

Internal submarine events can be categorised by the following classes:

- criticality accidents;
- primary heat transport system failures;
- secondary heat transport system failures;
- cooling-water system failures;
- electric system failures;
- instrument air system failures;
- hydraulic oil system failures;
- flooding;
- fires and explosions;

- sinking.

A discussion of each of these event categories follows below.

3.2.1.1 Criticality accidents

Criticality transients can be caused by different means, including

- control rod ejection from the core;
- the restart of an idle loop (injection of slug of cold water into the hot core);
- cold water injection by spurious actuation of the emergency coolant injection system;
- steam line break (causes overcooling transient);
- excessive steam demand (causes overcooling transient);
- reactor defuelling.

Control rod ejection

In a moored, decommissioned submarine, the reactor is in a guaranteed shut-down state, that is, the control rods are disconnected electrically and movement of the mechanical drive mechanism is impeded by means of mechanical stops. Furthermore, the coolant temperature is low (about 100 °C) and the coolant pressure is also low (1–1.5 MPa, cf. Section 2.4).

Accordingly, control rod ejection is not possible in a laid-up submarine.

Idle loop restart

In a moored, decommissioned submarine, the reactor coolant pumps are shut down and their power supply disconnected. Hence, the restart of a pump which could introduce a slug of cold water into the reactor core, is impossible. Furthermore, because the coolant temperature is maintained at about 100 °C, which is much lower than the normal operating temperature of about 300 °C and not much above the temperature of the water upstream of any stopped pump, an accidental pump restart is regardless not an event of concern in a decommissioned submarine.

Cold water injection

It is expected that in both first generation and second generation submarines, any existing emergency core cooling system would be a pumped system drawing water from a storage tank. The tank is not expected to be located inside the shield tank, and thus, the water inside it may be at a lower temperature than that inside the reactor, particularly during the winter. Established reactor safety practice is to ensure that the water in the storage tank is highly “poisoned” (that is, containing neutron-absorbing materials) in order to counteract any effects of the positive reactivity resulting from its possible injection into the reactor vessel. In a laid-up submarine, the storage tank is likely to be drained. However, since all the control rods are secured fully inside the core (thereby providing much excess negative reactivity, cold water injection is not an event of concern in a decommissioned submarine.

Steam line break
A steam line break causes a dramatic increase in the production of steam inside the affected steam generator(s), thus producing a cooling transient inside the core. The colder water entering the reactor from the inlet nozzle(s) may in turn cause a reactivity excursion. Because the moored, decommissioned submarine is shut down and does not produce steam, this event is not relevant.

Excessive steam demand
Excessive steam demand can occur when propulsion power is suddenly raised or by the spurious opening of the steam bypass valves. The opening of a bypass valve provides a path of much less resistance to the steam condenser, thus dramatically increasing the steam flow. The effect on the reactor is similar to that of the steam line break discussed above; similarly, because the submarine is shut down and does not produce steam, this event is not relevant.

Reactor defuelling
As demonstrated above, for moored, decommissioned submarines, criticality accidents may be eliminated as a possible source of concern when all rules and regulations are followed. The defuelling process, during which the reactor vessel and the submarine hull itself are open to the environment, is a possible exception, however, and this is discussed in more detail in Section 4.2 of this report.

3.2.1.2 Primary heat transport system failures

Primary system failures include the following classes of events:
- loss-of-coolant events;
- loss-of-coolant-flow events;
- fuel channel blockage.

Loss-of-coolant events
Loss-of-coolant accidents (LOCAs) may arise from various sources and means. The classic example is a break in a coolant line – a large LOCA. The design basis event is a guillotine break in the largest coolant line, which causes the most rapid discharge of coolant and uncovering of the reactor core. This event is necessarily analysed in detail during the design phase of the submarine because it sets the requirements for the emergency core-cooling system; however, its frequency of occurrence is estimated to be very low. More probable events are those associated with the failure of valve and pump seals or failures of steam generator tubes. These events fall into the category of small LOCAs and have a higher probability of occurrence. Spurious opening of pressure relief valves constitute another source of small LOCAs, particularly when they fail to close again once the overpressure is terminated.

In a moored, decommissioned submarine, the reactor is shut down, and the temperature and pressure of the coolant are maintained at low levels (about 100 °C and a few atmospheres, respectively). The driving force for a loss-of-coolant event is thus much reduced from that during normal operating conditions (about 300 °C and 15 MPa or 150 atmospheres).

Accordingly, the probability of a LOCA is much reduced from the corresponding value during high-power operation. Nevertheless, if reactor coolant is lost, fuel heat-up and damage is a possibility even in a shut-down reactor. Accordingly, this event needs to be further examined.

Loss-of-coolant-flow events

When the reactor is operating at high power, and a coolant flow interruption occurs, then there is an immediate risk of fuel heat-up. For this reason, the coolant pumps of most nuclear reactors are equipped with dual-drive motors. The motor windings that support full-speed operation are powered from the normal or “non-essential” electric buses, while the motor windings that support low-speed operation are powered from the “essential” buses. Therefore, if a power failure occurs causing the high-speed motors to stop, the pumps can continue to operate at low speed.

In a moored, decommissioned submarine, the reactor(s) and the pumps are shut down, and only natural circulation is required in order to remove the decay heat from the core. Loss of coolant flow is therefore not a concern.

Fuel channel blockage

When the reactor is operating at high power, coolant flow interruption to a single fuel assembly (or “channel”) is a serious concern because the event cannot be detected by the reactor control system; hence, the same amount of power must be removed with less flow. In such an instance, fuel heat-up is inevitable, and fuel damage may result.

In a moored, decommissioned submarine, the same event would be of far less concern because the power level is much less than one percent of full power. The fuel assembly affected by the flow blockage (or flow reduction) would heat up, but because the temperature of the core is low (about 100 °C compared to 500–600 °C when the reactor is at power), fuel damage would not be expected. Accordingly, this event is not of concern.

As demonstrated above, the only primary heat transport system event of concern is the loss-of-coolant event, which could lead to fuel damage or possibly to a core melt. This is further analysed in Section 4.1.

3.2.1.3 Secondary heat transport system failures

Secondary heat transport system failures include the following categories of events:

- steam line breaks;
- feedwater line breaks;
- loss of feedwater flow to the steam generators.

Steam line breaks

Steam line breaks are discussed in Section 3.2.1.1 with respect to criticality effects; however, they are also important in the removal of decay heat.

Assuming the reactor shuts down following a steam line break with the reactor at power, decay heat removal is assured for as long as there is feedwater in the feedwater storage tank. Eventually all the feedwater is consumed and an alternative decay heat removal pathway needs to be established. For a moored, decommissioned submarine, which does not generate steam, a long period of time (weeks) is required to reach this point due to the large inventory of feedwater relative to the decay heat generated. This event is not of concern for a moored, decommissioned submarine.

Feedwater line breaks

When the reactor is operating at high power, a feedwater line break is an important event as it causes the affected steam generator(s) to empty rapidly, thus losing the reactor heat sink. The same thing would happen in a moored, decommissioned submarine, except the likelihood of a feedwater line break would be small, as the feedwater pressure would be near one atmosphere. Leaks due to valve seal failures and pump seal failures would be more probable; however, the time scale for draining the affected steam generator(s) would be much longer. Ultimately, unless an alternative heat removal pathway is established, the primary heat transport system temperature and pressure will rise. When the coolant pressure eventually exceeds the pressure relief setpoint, the pressure relief valve(s) will open, and from here onwards, the event is similar to a small LOCA. Therefore, the fuel consequences of this event will be covered by the LOCA analysis.

Loss of feedwater flow to the steam generators

When the reactor is operating at high power, a loss of feedwater to the steam generators will cause the steam generator level to drop rapidly, and the event sequence would be similar to that of a feedwater line break.

3.2.1.4 Cooling water system failures

There are two key cooling water systems:

- the sea water cooling system, which supplies sea water to the condensers, the component cooling system heat exchangers, the lubrication oil coolers and the turbine/generator coolers;
- the component cooling system, which supplies fresh water to the shut-down cooling system heat exchangers, the purification system heat exchangers, the biological shield heat exchangers and other loads.

Sea water system failures

Sea water system failures include:

- loss of flow (pump failure, electric power failure, blockage of water inlets);
- pipe break downstream of the pumps.

The sea water system is the ultimate heat sink for the reactor. Partial or total impairment of the sea water system would have a significant impact on an operating reactor, but not on a shut-down reactor.

For the operating reactor, total impairment of the sea water system would lead to a pressurisation of the steam generators, and eventually to the opening of the steam safety relief valves. From this point onwards, the event sequence would be similar to that of the steam line break.

For a moored, decommissioned submarine, the decay power would be small enough that it could be dissipated by conduction in the condenser, and pressurisation of the steam generators would not occur. Hence, provided that the feedwater pumps continue to operate, the decay heat could be dissipated without active sea water cooling. Accordingly, this event is not a concern for a moored, decommissioned submarine.

Component cooling system failures

Component cooling system failures include:

- loss of flow (pump failures, motor failures, electric power supply failures and valve failures);
- loss of inventory (pipe break, heat exchanger leak, pump seal leak, valve leak, and so forth).

The system is a closed-loop, fixed-inventory system, hence, any reduction in inventory will cause a system impairment. For the moored, decommissioned submarine, this is only a problem if the decay heat is being removed by the shut-down cooling system or the purification cooling system. Nevertheless, even with the secondary side of the shut-down cooling heat exchangers empty, it may be possible to dissipate the decay heat through conduction and convection. Hence, this event is not of concern for a moored, decommissioned submarine.

3.2.1.5 Electric system failures

There are two key options for the removal of decay power from the core:

- via the steam generators (requires the operation of the feedwater system and the sea water system);
- via the shut-down cooling system (requires the operation of the component cooling system and the sea water system).

The first option does not require operation of the reactor cooling pumps and relies on natural circulation to transfer decay heat from the core to the steam generators. At the very minimum, it requires operation of a feedwater pump and a condenser extraction pump to remove the heat from the steam generators. Because the condensers have a large surface area and mass, it is unlikely that the sea water pumps are required to transport the decay heat from the condenser to the sea. This does indeed appear to be the selected option for Russian submarines [Khlopkin *et al.*, 1997].

The reliability of the decay heat removal function, however, is dominated by the reliability of the electric supply system(s). A brief interruption of electric power may not have a significant impact on fuel cooling, but a prolonged interruption would cause the temperature and pressure of the reactor coolant system to rise. When the coolant pressure exceeds the pressure relief setpoint, the pressure relief valve(s) will open and from there onwards, the event sequence is similar to that of a small LOCA. Therefore, the consequences of this event for the nuclear fuel will be covered by the small LOCA analysis in Section 4.1.

3.2.1.6 Instrument air system failures

Instrument air is commonly used to keep pressure relief valves closed. Air pressure is required to counter the force generated by a mechanical spring inside the valve. If instrument air pressure is reduced, the spring force opens the valve and holds it open. This type of valve is probably used for pressure relief in both the primary and secondary heat transport systems. Hence, loss of instrument air would cause a small LOCA on the primary side and a continuous steam discharge on the secondary side. This is a serious failure if the reactor is at power, but it is less critical if the reactor is shut down. In a moored, decommissioned submarine, natural circulation of the reactor coolant would cease immediately after the pressure relief valves open, and the reactor coolant may begin to boil. The consequences of instrument air system failures are covered by the small LOCA analysis in Section 4.1.

3.2.1.7 Hydraulic oil system failures

The hydraulic oil system is essential for manoeuvring the submarine, but it is unlikely to be used in areas important to reactor safety.

3.2.1.8 Flooding

The nuclear propulsion system of a first generation nuclear submarine is contained in three compartments: the reactor compartment, the machinery compartment and the electric motors compartment (cf. Figure 2.2). Flooding of any one of these compartments would have a significant impact on reactor safety, but would not cause the submarine to sink.

It is assumed that the reactor compartment contains all the nuclear systems, that is, all systems interfacing with the reactor. This includes heat exchangers for the biological shield, the shut-down cooling system and the purification system. The component cooling system and the sea water system, along with the steam turbines, hydraulic compressors and air compressors are assumed to be in the machinery compartment. Finally, electric motors for driving the propeller shafts, batteries and diesel generators are assumed to be in the electric motors compartment.

Clearly, for a moored, decommissioned submarine, flooding of any of these compartments will affect the decay heat removal function. For example, flooding of the electric motors compartment will cause a loss of electric power; hence, the consequences would be as described in Section 3.2.1.5. Flooding of the machinery compartment would halt the feedwater and condensate extraction pumps; hence, the consequences would be as described in Section 3.2.1.3. Finally, flooding of the reactor compartment may not be as critical as there are no moving parts required for decay heat removal in this compartment.

3.2.1.9 Fires and explosions

Fires are most likely to occur in the machinery and electric motors compartments where there are combustible materials such as hydraulic oil, lubrication oil, diesel fuel, and so forth. It is unlikely that a fire would occur in the reactor compartment which contains only small quantities of combustible materials. An explosion (other than from weapons, which are assumed to have been removed from any decommissioned submarine) would most likely occur in the electric motors compartment where there is the potential both for a source of combustible gases (hydrogen from the electric batteries) and for a source of ignition (spark from electric motors). It is assumed that combustible materials have been removed from moored, decommissioned submarines [Khlopkin *et al.*, 1997].

If a fire occurred in the machinery or electric motors compartment, its effects on decay heat removal most likely would be the same as the effects caused by flooding. Both the flooding and the fire would impair the motors of the pumps required to remove decay heat. An explosion would not be possible in a laid-up submarine stripped of weapons and explosive materials.

3.2.1.10 Sinking

A decommissioned nuclear submarine may sink due to the development of a major leak in the hull. This may be due to corrosion, for example, or an explosion which damages the hull. If the sinking occurs at the base, it should be relatively easy to repair the hull and recover the submarine.

A submarine may also sink at open sea during transport from one base to another. In this case it may be considerably more difficult to recover the submarine. At the bottom of the sea the materials of the submarine will gradually corrode, and radioactive materials will ultimately be released into the surrounding environment. However, experience with both sunken Soviet and American nuclear submarines indicates that the release of radioactivity is very slow and small [NATO, 1995a].

Submarine reactors are necessarily built to withstand rough combat conditions. This suggests that even if a submarine sinks in a non-upright position, one would expect the reactor fuel assemblies not to loosen or in any other way change their relative positions.

A special case of sunken decommissioned nuclear submarines is that of the non-defuelled submarine and reactor compartments that the Soviet Union dumped near Novaya Zemlya between 1965 and 1981 (cf. Section 2.5).

3.2.2 External events

External submarine events can be categorised by the following classes of events:
- ship collisions;
- falling objects;

- grounding or beaching.

These events are further discussed below.

3.2.2.1 Ship collisions

It is possible that a moored, decommissioned submarine could be struck by a ship, particularly if the vessel is moored in an area of high shipping traffic. Ship collisions are not uncommon in high-traffic areas, particularly during stormy periods or periods of low visibility. Indeed, in May 1997, a decommissioned Project 670A/Charlie-I class submarine sank at the submarine facilities in Kamchatka after it was hit by another vessel [Handler, 1998]. The submarine had been defuelled before the accident occurred.

The concern arising from ship collisions is the potential for breaching both the containment boundary (the hull) and the primary coolant boundary. Should this occur, the ensuing loss of coolant could give rise to significantly higher releases of radionuclides to the surrounding environment than any release caused by internal events. However, the likelihood of such a release is very small for the following reasons:

- the submarines are built to withstand very large shock loads during combat;
- they are moored in remote locations, such that the threat of external aggressions (collisions and falling objects) is very small.

Nevertheless, if a collision should occur thereby damaging the containment and causing a small LOCA, the impact on the reactor core would not be greater than that arising from a small LOCA (Section 3.2.1.2). It is possible, however, that the flooding resulting from a breach of the reactor compartment would prevent severe core damage by keeping the core covered by water at all times.

A collision could cause damage to other compartments. In that case, the compartment would flood, and the consequences would be similar to those discussed under flooding (Section 3.2.1.8). There is also the possibility that a collision could cause the submarine to sink (see Section 3.2.1.10).

3.2.2.2 Falling objects

In a mooring location with many decommissioned submarines, the presence of high-lift cranes is almost certain, particularly for purposes of defuelling and dismantling. Hence, the possibility that a heavy object falls on a submarine cannot be discounted. However, the impact of such an event is not likely to be more severe than a ship collision (Section 3.2.2.1).

3.2.2.3 Grounding or beaching

Grounding or beaching are not a concern for a moored, decommissioned submarine.

3.3 Events to be further analysed

As discussed in Section 3.2 above, the only concern arising from a moored, decommissioned submarine is a small core heat-up or LOCA event. Core overheating can occur primarily by draining of the pressure vessel. This can occur by a direct event (such as a coolant leak) or indirectly (for example, through the loss of electric power, which in turn would cause a disruption of the removal of decay heat from the core, which in its turn would cause reactor coolant to be lost through the pressure relief valves). The small loss-of-coolant accident is thus taken as the reference event, and the results of this analysis may be viewed as an upper limit for the consequences arising from any other internal events discussed above. The small LOCA is the topic of Section 4.1 below.

In general, the reactor core is a critical assembly which is held subcritical by engineered features. The modifications described in Section 3.1.6 for reactors on board decommissioned submarines should prevent the criticality events discussed above from occurring. During defuelling, however, the submarine hull and the reactor vessel are open to allow fuel removal, and deviations from safe operating procedures may result in a criticality event, that is, the fissile material still contained in the fuel may undergo a chain reaction. Such an event would be short-lived, but a fraction of the spent fuel and the activated core structure may be volatilised, and significant quantities of fission products may be released to the surrounding environment. The energy produced by the chain reaction would facilitate the dispersion of the radioactive material. Such an accident would result from the violation of the safe operating procedures; it can consequently be prevented by strict adherence to all procedures. The procedures proposed by Russia for defuelling, whereby the reactor vessel is fully drained of water, would be effective in preventing this kind of accident. Nevertheless, due to the significant amount of radionuclides released in a criticality accident, this accident scenario is also analysed below (Section 4.2).

It is not obvious whether or not the risk of a criticality accident is aggravated by the long storage periods that many of the submarines experience. On the one hand, the risk is reduced in that after a long period of storage the core can stay drained indefinitely; therefore, there is no time pressure to perform the defuelling activity. The amount of radionuclides that would have been released in an accident also necessarily decreases with time due to radioactive decay. On the other hand, the risk of a defuelling accident is increased by the long storage time because the many mechanical parts of the reactor plant necessarily deteriorate over the years (by corrosion, for example).

External events are excluded from further analysis because:
- they are site dependent, and site specific information is not available;
- the core damage would anyway not exceed that caused by a small LOCA.

4 ACCIDENT ANALYSES

This chapter contains detailed discussions of the two significant accident scenarios identified in the previous chapter: core heat-up/loss-of-coolant accidents and criticality accidents.

4.1 Loss-of-coolant accidents

A small loss-of-coolant accident (LOCA) is one of the classic reactor accidents that can occur even in a decommissioned submarine. Because the radiological consequences of a small LOCA can be substantial, it is one of the foremost accident scenarios to be considered. As described in Chapter 3, core heat-up may also be caused by other events than a loss of coolant, but the effects of a small LOCA set an upper limit for the consequences of all core heat-up accidents. The analysis outlined below is descibed in [Kupca and Natalizio, 1997].

4.1.1 Initial reactor plant state

The consequences of a given LOCA are governed primarily by the state of operability of the reactor plant and the availability and vigilance of the operations and maintenance staff. It has been assumed that the submarine is in a “mothballed” state, that is, with the exception of equipment necessary for maintaining decay-heat removal, all other systems and equipment are assumed to be inoperable.

Prior to the event that initiates the accident, the core decay heat is assumed to be removed by natural circulation of the primary coolant. Forced circulation of feedwater is provided in the secondary circuit to transport the decay heat from the steam generators to the steam-turbine condensers. Forced circulation of sea water through the condensers is not necessary to transport the decay heat from the condensers to the sea; this can be achieved by passive means.

4.1.2 Event initiation and postulated sequence

The initiating event is a small, undetected coolant leak. The leak remains undetected, and eventually the undrained water inside the reactor vessel is evaporated, exposing the reactor core to a mixture of steam and air. Once the reactor core is fully exposed, the fuel begins to heat up; melting is then a possibility, unless the heat can be transferred from the reactor core to the vessel and from the vessel to the reactor compartment by passive means.

The reactor vessel is located inside the shield tank, but it is presumably thermally isolated from the tank by an air gap. Therefore, the first possible avenue for the transfer of decay heat to the reactor compartment is through the reactor head. As shown in Figure 4.1, once heat is transferred to the reactor compartment, natural convection would transfer it to the sea. An alternative pathway for the transfer of heat is through the bottom of the shield tank, which is in contact with the submarine hull (see Figure 4.2). Both pathways are assessed in Section 4.1.4 below.

In the hypothetical event that insufficient heat is removed by either of these two pathways, the reactor fuel would continue to heat up until the hottest elements melt and drop to the bottom of

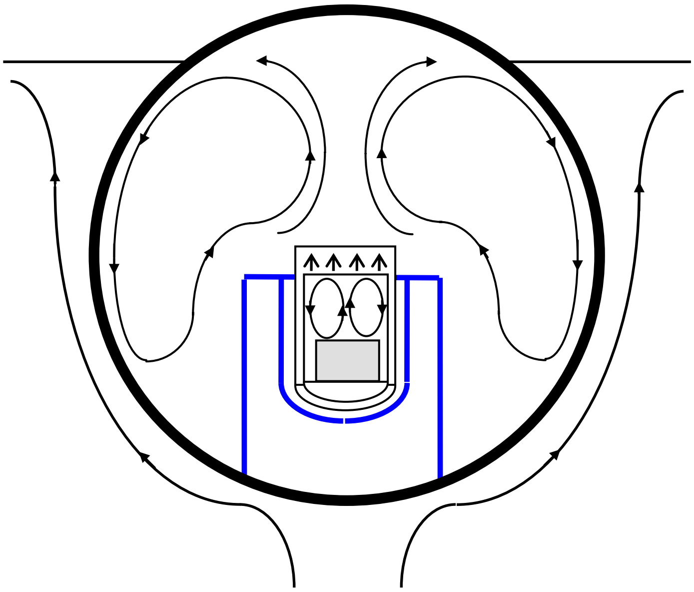

Figure 4.1. Transfer of decay heat from the reactor to the sea via the reactor compartment.

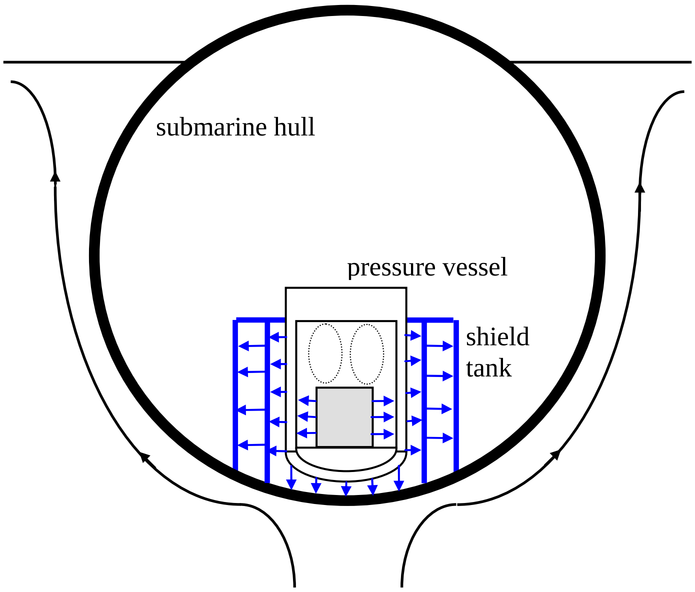

Figure 4.2. Pathway for the removal of decay heat from the shield tank.

the reactor vessel. Were this to happen, more heat would be radiated from the bottom of the pressure vessel to the bottom of the shield tank, thereby most likely preventing the melting of the entire core.

4.1.3 Initiating event frequency

At a given mooring site, the initiating event frequency is governed by the following factors:

- the probability of component or equipment failure (valve or pump leak, pipe break, and so forth) occurring in a single submarine reactor plant;
- the number of reactor plants per submarine;
- the probability of a sustained loss of electric power;
- the number of submarines moored in the same location.

For purposes of this analysis, it is assumed that in some laid-up submarines, electric power is required for decay-heat removal; hence, if electric power is lost for long periods, the coolant in the reactor vessel will boil off via the pressure relief valves.

The leaking of reactor coolant through piping flange connections, valve stem seals, or pump seals is more likely to occur in first generation than in second generation submarines. This is due to the more distributed nature of the reactor cooling system of the first generation submarines and the large number of components and piping connections associated with it. It is presumed that second generation submarines have “canned” pumps and no valves in the primary cooling system. Without details of the reactor plant design, however, it is not possible to quantify the difference. Consequently, only a generic order of magnitude estimate of event frequency can be performed.

A key factor affecting the small LOCA frequency is the relatively low coolant pressure that reportedly prevails in the decommissioned submarines (1–1.5 MPa) [Khlopkin *et al.*, 1997].

Component leakage stems primarily from valves and pumps which have a leakage frequency of an estimated 10^{-2} per component per year. (This number actually applies to Canadian nuclear power plants and reflects small leaks from components operating at high pressure (about 10 MPa).) The value may be at least 10 times smaller for large leaks and another 10 times smaller for operation at about 1 MPa. Therefore, assuming that there are 10 components that could leak (very conservative assumption for reactors of second generation submarines), the coolant leakage frequency may be as high as about 10^{-3} per reactor per year.

Most laid-up submarines have two reactor plants; a conservative estimate for the small LOCA frequency would then be about $2 \cdot 10^{-3}$ per submarine per year. For a specific mooring site containing ten laid-up submarines, the combined small LOCA frequency would thus be on the order of $2 \cdot 10^{-2}$ per year.

As mentioned earlier, failure of shore-based electric power supplies can also lead to a loss of coolant from the reactor vessel. Since the heat-up of the core takes several hours (on the order of ten hours), a disruption of shore-based electric power for less than a few hours would not lead to fuel melting. Power interruptions lasting only a short time are generally very common, but loss of power for an extended period of time is very rare. In the lack of grid reliability data for the mooring locations of decommissioned submarines, it is assumed that a loss of grid power for more than eight hours has a frequency of five per one hundred years ($5 \cdot 10^{-2}$ per site per year). Hence, a core heat-up event is about as likely to occur from the loss of shore-based electric power as from coolant leakage.

4.1.4 Accident consequences

The most probable consequence of an unmitigated small coolant leak would be a contained partial core melt, unless the passive pathways for decay heat removal (cf. Section 4.1.2) are capable of removing the entire decay power.

As depicted in Figure 4.1, the reactor pressure vessel is completely surrounded by the shield tank, except at the top. Furthermore, the air gap between the pressure vessel and the shield tank provides good thermal isolation. Accordingly, it may appear that the only feasible heat transfer pathway between the core and the reactor compartment is via the pressure vessel head, despite the fact that it is covered by a thick layer of thermal insulation (which may be removed during the decommissioning period). As shown in the figure, heat is transferred from the reactor to the head of the pressure vessel by natural convection. Decay heat would be picked up from the top of the reactor core by convection cells and transferred to the bottom of the pressure vessel head.

However, decay heat may also be transferred from the pressure vessel to the shield tank and from the shield tank, which is in contact with the hull, directly to the sea. Figure 4.2 indicates this mode of heat transfer. Accordingly, two sets of calculations have been performed: heat transfer via the reactor compartment, and heat transfer via the shield tank.

The analysis is based on the second generation reactor model. Prorating the results for first generation submarines on the basis of power will therefore include a substantial factor of conservatism (cf. Section 3.1). The calculations assume that the pressure vessel is completely drained of coolant (as long as it contains water, excessive heat-up of the fuel is impossible).

4.1.4.1 Heat transfer via the reactor compartment

The analysis of heat transfer via the reactor compartment has been performed in two steps. The first step is to demonstrate a heat removal capability from the reactor compartment to the sea, and the second step is to demonstrate a heat removal capability from the pressure vessel head to the reactor compartment.

Heat transfer from the reactor compartment to the sea

It is assumed that a total decay power of 13.5 kW (estimated decay power for a second generation reactor one year after shut-down, cf. Table 3.3) must be transferred from the reactor compartment to the sea by passive means only, that is, by natural convection inside and outside the reactor compartment (cf. Figure 4.1). The heat transfer coefficient for free convection in air (inside) and in water (outside) was assumed to be 6 W/m^2 °C for both. This value is at the low end of the reasonable range and will therefore overestimate the temperature drop required to reject the decay power.

The hull was assumed to consist of 5 cm thick steel covered with a 1 cm thick layer of acoustic tiles. The tile material is likely to be classified, but for purposes of heat transfer it is assumed to have the same conductivity as rubber (0.15 W/m °C at room temperature). The type of steel utilised for the submarine hull is also likely to be classified, but the thermal conductivity of 15 W/m °C used in the analysis does not vary significantly for different steels.

Table 4.1. Thermal resistance across reactor vessel head.

	Thermal resistance (°C/kW)
Air film above head	16.7
Asbestos layer	593
Steel head	13.6
Steam film below head	1.67
Total	625

Using the above heat transfer parameters, and assuming that the reactor compartment is 10 m in diameter and 10 m in length, the temperature drop required to transfer 13.5 kW by natural convection is found to be 18 °C. Hence, if the sea water is at 10 °C, the inside of the reactor compartment would be at 28 °C. The large surface area of the hull (about 300 m^2) makes it possible to transfer all of the decay heat even though the acoustic tiles act as a thermal insulator.

Heat transfer from the reactor vessel to the reactor compartment

The internal diameter of the second generation reactor vessel is assumed to be 2 m; hence, the heat transfer area of the pressure vessel head is 3.1 m^2. Furthermore, the head is assumed to be 40 cm thick and covered with 21 cm of thermal insulation. For purposes of thermal conductivity, the insulation is assumed to be asbestos, which has a thermal conductivity of 0.2 W/m °C at temperatures around 200 °C.

The heat transfer coefficient for free convection above the pressure vessel head insulation is taken to be 30 W/m^2 °C (a value at the high end of the range, due to the higher temperatures anticipated). The value used for free convection of steam inside the pressure vessel is 300 W/m^2 °C (also at the high end of the range, due to the high temperatures anticipated). The thermal resistance for this heat transfer pathway is given in Table 4.1.

As shown in Table 4.1, the total thermal resistance is about 620 °C/kW. This means that the transfer of 13.5 kW requires a total temperature drop of about 8000 °C. Clearly, the asbestos insulating layer makes it impossible to remove decay heat through the pressure vessel head. However, if the decommissioned submarine has been (or were to be) stripped of the thermal insulation above the pressure vessel head, then the required temperature drop to remove 13.5 kW through the pressure vessel head would be about 430 °C. In that case, if the air temperature inside the reactor compartment is 30 °C, then the steam temperature inside the pressure vessel, just below the head would be on the order of 500 °C. If the core temperature is limited to 1500 °C, then there would be a temperature difference of about 1000 °C to drive the natural convection cells above the reactor core. This appears to be a substantial driving force providing confidence that this pathway would be capable of removing the decay heat without causing the reactor fuel to melt. However, it is unknown whether the insulation above

Table 4.2. Thermal resistance across shield tank and hull (conduction only).

	Thermal resistance (°C/kW)
Shield tank plate	0.17
Hull plate	0.35
Rubber tiles	6.9
Water film below rubber tiles	1.7
Total	9.3

the pressure vessel head is indeed routinely removed as part of the submarine decommissioning process.

4.1.4.2 Heat transfer via the shield tank

The first step is to demonstrate a heat removal capability from the reactor fuel to the shield tank. The second step is then to demonstrate a heat removal capability from the shield tank to the sea.

Heat transfer from the shield tank to the sea

The model for this calculation is shown in Figure 4.2. The following assumptions have been made:

- the submarine hull is 5 cm thick;
- the rubber tiles are 1 cm thick;
- the *Sevmorput* shield tank base is 3.5 m in diameter (10 m^2 area) and 1 cm thick;
- the conductivity of the shield tank plate is 15 W/m °C;
- the conductivity of the hull plate is 15 W/m °C;
- the conductivity of the rubber tiles is 0.15 W/m °C;
- the heat transfer coefficient of the water film below the rubber tiles is 60 W/m^2 °C.

The resulting thermal resistance for this heat transfer pathway is given in Table 4.2. The thermal resistance of the rubber tiles dominates the result. The total thermal resistance is about 9 °C/kW. Hence, a transfer of 13.5 kW would require a temperature drop of about 120 °C. Consequently, if the sea water is at 10 °C, the temperature of the shield tank plate under the pressure vessel would have to be at least 130 °C to transfer 13.5 kW of decay power if this power is radiated to the shield tank plate. The temperature required to radiate 13.5 kW of decay power from the bottom of the pressure vessel is about 300 °C. Heat must be conducted from the wall of the reactor pressure vessel down to the bottom in order to be radiated to the shield tank plate underneath the pressure vessel. It is therefore assumed that the wall of the reactor pressure vessel would be at 500 °C, a temperature which is expected to be adequate for achieving the required heat transfer.

Figure 4.3. Typical radial temperature profile across the nuclear reactor core (positions 1 through 13), the pressure vessel (14 through 19) and the shield tank (20). The calculations apply to a second generation reactor with a decay power of 4.5 kW.

Heat transfer from the fuel to the pressure vessel and the shield tank

This calculation was designed to determine the temperature of the fuel when the wall of the pressure vessel is maintained at 500 °C. The temperature of the inner shield tank wall was also calculated. This calculation is based on the ring model of the nuclear core shown in Figure 3.4. For a second generation submarine, the model has 13 fuel rings, a neutron reflector ring, a core barrel ring, three shield rings, a pressure vessel ring and a shield tank ring. Heat is transmitted from the central fuel ring to the outer fuel rings and ultimately to the shield tank ring by thermal radiation. A typical temperature distribution is shown in Figure 4.3.

The central fuel assembly reaches the highest temperature. Figure 4.4 shows how this temperature varies as a function of decay power. The melting point of UO_2 is 2840 °C. However, the melting point of zircalloy, which may be used as cladding material, is 1825 °C; hence, core structural damage would begin to take place at this lower temperature. Accordingly, 1800 °C is set as the maximum temperature limit to avoid core damage. From Figure 4.4, the maximum decay power for preventing core damage is then about 5 kW, which according to Table 3.3 corresponds to a second generation reactor approximately three years after shut-down. U-Zr metallic fuel has a higher melting point than 1800 °C. The analysis in this section is therefore conservative if its results are applied to U-Zr fuel. U-Al fuel, if such is used, has a lower melting point, however, and would be more vulnerable than indicated in this analysis.

Figure 4.5 shows the core heat-up time as a function of decay power. For a decay power level of 5 kW or less, the time it takes the reactor core to heat up to the reference temperature given by Figure 4.4 is greater than 40 hours. The starting point for this calculation is a drained pressure vessel, and the calculated time does not include the time required for the vessel to be fully drained, which is on the order of 10, 20 and 30 days at one, two and three years after final

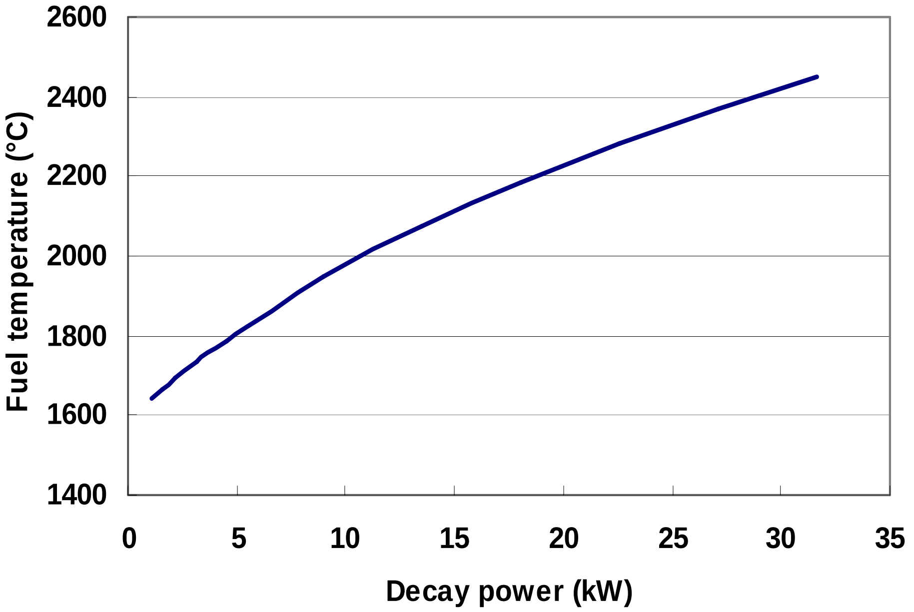

Figure 4.4. Temperature of the central fuel assembly as a function of decay power for a second generation nuclear submarine.

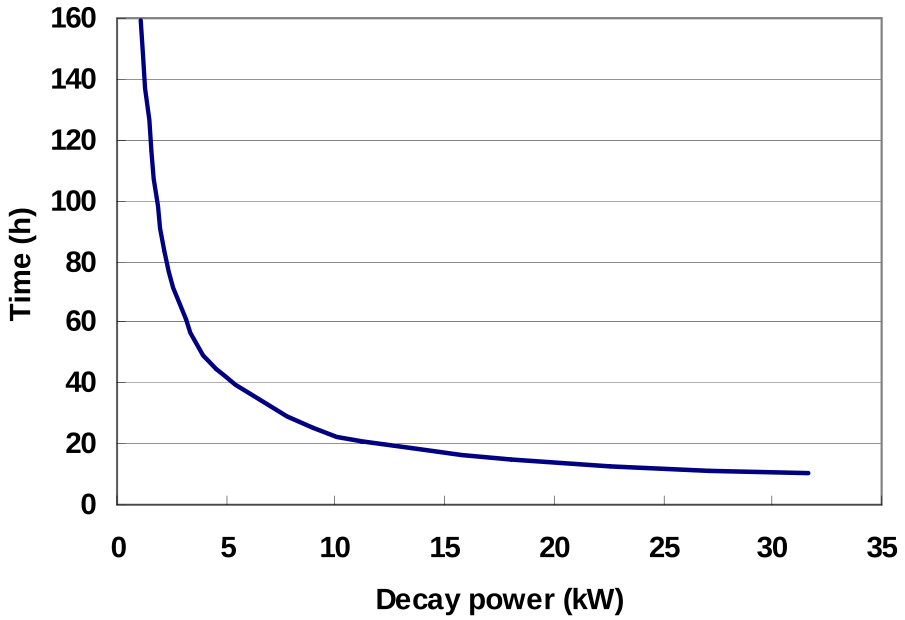

Figure 4.5. Core heat-up time as a function of decay power. The curve shows the necessary time for heating to the maximum temperature as indicated in Figure 4.4 or to 1800 °C (whichever is the lower) for any given decay power.

reactor shut-down, respectively. The estimated drainage time is based on the evaporation of 5000 kg of water, a smaller quantity than what is likely to be inside the pressure vessel. Figure 4.5 also shows that the minimum heat-up time is about ten hours. Therefore, a loss of electric power for just a few hours would not have any significant consequences for moored, decommissioned submarines.

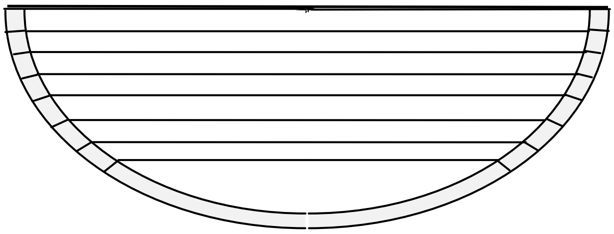

Figure 4.6. Model of pressure vessel bottom used for heat conduction calculations.

Table 4.3. Pressure vessel bottom heat transfer parameters used for heat conduction calculations (cf. Figure 4.6). The heat transfer elements are numbered from the top downwards.

Heat transfer element	Outer radius (m)	Thickness (cm)	Radiating area (m^2)	Heat conduction resistance (°C/kW)
1	0.99	6.2	0.39	3.3
2	0.97	6.2	0.39	3.3
3	0.95	6.9	0.41	3.8
4	0.93	6.9	0.41	3.8
5	0.90	18.0	0.99	10
6	0.81	19.0	0.95	12
7	0.65	20.0	0.82	16
8	0.62	—	1.33	—
Total			5.69	52

Heat transfer from the pressure vessel wall to the shield tank

For the decay heat to be transferred to the sea, it must first be transferred to the shield tank. Two pathways are available (cf. Figure 2.6 and Figure 4.2):

- radiation from the pressure vessel bottom to the shield tank plate directly below it;
- radiation from the pressure vessel walls to the inner walls of the shield tank.

Radiant heat transfer from the bottom of the pressure vessel to the shield tank plate below it requires the decay heat to be transferred to the bottom of the vessel by conduction along its walls. The conduction calculation is complicated by the ellipsoidal geometry of the pressure vessel bottom and the fact that heat is lost by radiation along the conduction path. The model used is shown in Figure 4.6. The ellipsoid was sliced into seven annular rings and one “bowl” slice at the bottom. The dimensions of the annular rings and the bowl are given in Table 4.3. The first four elements are thinner because the thermal gradients are higher in the top region. The total radiation area is 5.7 m^2. Assuming no radiation heat transfer from the annular elements, the total resistance to conduct heat to the “bowl” (which has the largest radiation area) is 52 °C/kW. However, because of the radiation heat transfer from the annular elements, the effective resistance is much lower.

Table 4.4. Thermal resistance across shield tank and hull (including air convection and conduction).

	Thermal resistance (°C/kW)
Air film above shield tank plate	17
Shield tank plate	0.17
Hull plate	0.35
Rubber tiles	6.9
Water film below rubber tiles	1.7
Total	26

This model demonstrated that it is possible to conduct sufficient heat to the lower elements to radiate a maximum of about 15 kW to the shield tank bottom. Clearly, there is no problem transferring 5 kW of decay power, corresponding to a second generation reactor three years after shut-down, from the pressure vessel to the shield tank plate below the pressure vessel.

It is unavoidable that a significant portion of the decay power radiated to the pressure vessel will be further radiated to the inner walls of the shield tank. Radiant heat transferred to the inner walls of the shield tank will cause natural convection cells to be established inside the shield tank compartments. These compartments are normally filled with water, but even if the tank compartments are drained, air convection currents would be established and heat transferred from the inner walls to the bottom plates. From the bottom plates, the heat can be transferred to the sea by conduction through the hull. As shown in Table 4.4, the thermal resistance for this pathway is about 26 °C/kW. (The assumptions here are the same as those used to generate Table 4.2.) The heat transfer coefficient for the air film above the shield tank plate is assumed to be 6 W/m^2 °C. Therefore the transfer of 13.5 kW of decay power, corresponding to a second generation reactor one year after shut-down, would require a temperature drop of about 350 °C.

In short, two pathways exist to remove the decay heat from the pressure vessels and to transfer it to the sea. The two pathways combined ensure that decay power from any first generation or second generation submarine that has been laid up for storage can be removed from the pressure vessel. The limiting pathway is from the fuel to the pressure vessel; this sets an upper limit of about 5 kW of decay power that can be removed entirely by passive means.

Figure 4.7 shows the decay power as a function of time after reactor shut-down for both first generation and second generation reactors. It also shows the 5 kW limit for transferring decay heat by passive means only. This figure indicates that the decay power of a second generation reactor can be removed by entirely passive means about three years after reactor shut-down. For first generation reactors, the time indicated by Figure 4.7 is about 1.5 years; however, because the second generation model overestimates fuel temperatures for a first generation reactor, the time is likely to be closer to one year.

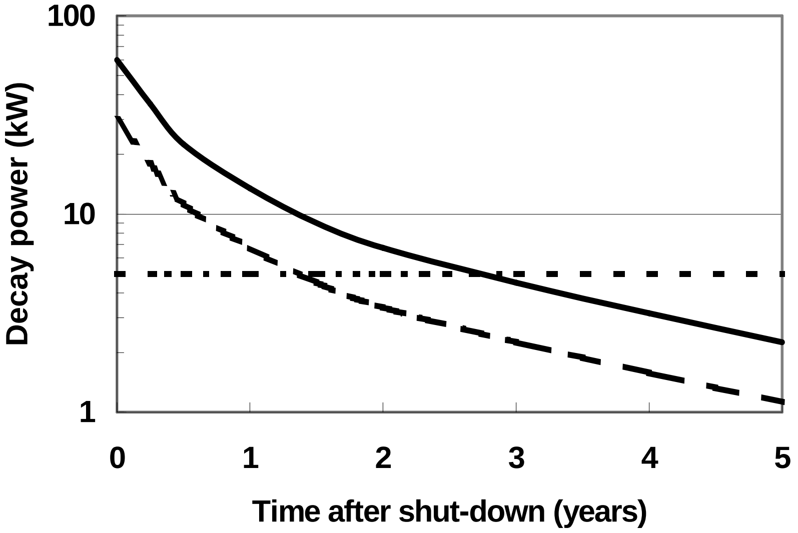

Figure 4.7. Passive safety regime for decay heat removal. The curves show estimated decay power for first generation reactors (dashed curve) and second generation reactors (solid curve). The decay power estimates are from Table 3.3 and assume average reactor operation at 25% of full power. The dotted line indicates the upper limit of 5 kW of decay power that can be removed entirely by passive means.

4.1.5 Core melt frequency

There are two major contributors to the frequency of core heat-up events: loss of electric power to the feedwater pump(s) and a small loss of coolant. A loss of electric power for more than eight hours was postulated above to occur with a frequency of $5 \cdot 10^{-2}$ per year. The only mitigative action possible is to restore shore-based power with emergency diesel generators. The unavailability for such equipment is assumed to be 10^{-2} per reactor; hence, the core melt frequency becomes $5 \cdot 10^{-4}$ per year per reactor. Assuming that the lay-up rate of second generation submarines per site is one per year, then the number of submarines susceptible to a core melt per site during any year is two (during the first year after shut-down, the submarines have not yet been placed in long-term storage; more than three years after shut-down, all decay heat can be removed by entirely passive means). Further assuming that there are two reactors per submarine, the core melt frequency for any site becomes $2 \cdot 10^{-3}$.

With respect to small loss of coolant accidents, the initiating event frequency is $2 \cdot 10^{-2}$ per site per year (cf. Section 4.1.3). The only mitigative action possible is to refill the cooling system as soon as it is discovered that the pressure is too low. Even fire water could be used for this purpose. Assuming the unavailability of replacement water is 10^{-2} (a figure which is likely to be dominated by the probability of human error), the core damage frequency becomes $2 \cdot 10^{-4}$ per site per year. Consequently, loss of electric power dominates the core melt frequency.

4.1.6 Consequences of a core melt

Given that a core melt cannot be completely discounted, and that the core melt frequency is non-negligible, it is necessary to determine the consequences of such an event if one were to occur.

The most likely scenario is a partial core melt whereby the innermost fuel assemblies would melt and drop on top of the horizontal shield plate. The number of assemblies that would melt depends on the decay power (that is, on the time after final reactor shut-down). It is assumed that eventually the molten fuel would relocate to the bottom of the pressure vessel. As the temperature of the pressure vessel bottom rises due to contact with the fuel, more heat is radiated to the bottom of the shield tank, and more heat is conducted to the sea. It is possible, but highly unlikely, that the fuel would melt through the bottom of the pressure vessel. Nevertheless, if this were to happen, the fuel would drop to the bottom of the shield tank where it would be well cooled thereafter. The integrity of the hull and reactor compartment would be maintained.

The molten fuel would release fission products inside the pressure vessel, and a small fraction of fission products could even escape into the reactor compartment through the coolant leakage path. However, since there is no pressurisation of the compartment, there would be no significant radionuclide release to the surrounding environment.

4.2 Criticality accidents

Criticality accidents that occur during defuelling are the type of accidents which is most likely to result in contamination of the surrounding areas, for during the defuelling process, the reactor is open and radioactive materials resulting from a reactor excursion can readily escape. The former Soviet Union reportedly had two refuelling accidents, both of which fortunately took place after the new fuel had been inserted such that the release of radioactivity was limited only to part of the fission products that were produced during the reactor excursion. In the case of decommissioned submarines, spent nuclear fuel, which generally contains large amounts of fission products, is involved.

As discussed in Section 4.2.6, several other criticality accidents occurred in the Soviet Union. However, these accidents were such that they are most unlikely to take place in decommissioned submarines. In general, criticality accidents are most likely to occur during construction and maintenance of the submarines at shipyards or during refuelling or defuelling when fuel or control rods are moved.

A special case is that of the Soviet Project 645/modified November class submarine *K-27* which was scuttled near Novaya Zemlya with one damaged and one intact liquid metal cooled reactor. Some time in the distant future, corrosion will cause water to move into the reactor and thereby improve neutron moderation. This may cause the reactor to go supercritical [IAEA, 1997a].

Below, a defuelling accident is examined, and an attempt is made to assess the amount of radioactivity released to the environment as well as the probability per defuelling of experiencing a criticality accident [Ølgaard, 1996b]. (The discussion would also apply to a refuelling accident, but decommissioned submarines are not refuelled.) An accurate assessment of such an accident is possible to make only if the necessary data for the reactor involved are available. Since this is generally not the case for submarine reactors, an attempt has been made here to estimate the release of radioactive materials by use of a simpler approach which still should reflect reasonably the physical realities.

4.2.1 Supercriticality

The reactor physics term which indicates whether a reactor is critical, subcritical or supercritical is the *effective multiplication factor* k_{eff}. This factor is defined as the ratio between the number of neutrons in a reactor in a given neutron generation and the number of neutrons in the preceding generation. If the number of neutrons is n in one generation, it will be $k_{eff}n$ in the next generation.

- If k_{eff} is larger than 1, the number of neutrons in the reactor will increase steadily. The reactor is *supercritical.*
- If k_{eff} is equal to 1, the number of neutrons in the reactor is constant in time. The reactor is *critical.*
- If k_{eff} is less than 1, the number of neutrons in the reactor will decrease steadily. The reactor is *subcritical.*

Instead of k_{eff} the *reactivity* ρ may be used. It is defined as

$$\rho \equiv \frac{k_{eff} - 1}{k_{eff}} \approx k_{eff} - 1 = k_{ex}$$

where k_{ex} is called the *excess k.*

More than 99% of the neutrons produced by fission are emitted immediately after the fission process. However, a small fraction β of the neutrons, the so-called *delayed neutrons*, are emitted up to several minutes after the fission process took place. For fuel highly enriched in ^{235}U, such as that used in submarines, β is equal to 0.007. When the delayed neutrons are taken into account, the time between two neutron generations, $t_{g,dn}$, is about 0.1 s. Provided k_{eff} is only slightly larger than 1, the neutron population of a supercritical reactor will increase exponentially according to the following formula:

$$n(t) = n_o \exp\{(k_{eff} - 1)t / t_{g,dn}\} = n_o \exp\{(k_{eff} - 1)t \cdot 10\ \mathrm{s}^{-1}\}$$

Here t is the time, and n_o is the number of neutrons at $t = 0$. The increase indicated by the formula is fairly slow and can easily be handled by the control system.

As mentioned above, if n is the number of neutrons in one generation, the number of neutrons in the next generation is $k_{eff}n$. Of these neutrons, $\beta k_{eff}n$ are delayed neutrons while $(1-\beta)\,k_{eff}n$ neutrons are prompt neutrons, emitted immediately after fission.

If $(1-\beta)\,k_{eff}n$ is larger than n, that is,

$$(1-\beta)\,k_{eff} > 1 \quad or \quad k_{eff} > \frac{1}{1-\beta} = 1.007$$

the reactor is called *prompt critical* since it is critical on the prompt neutrons alone, and now the time t_g between two neutron generations is not influenced by the delayed neutrons. For a light-water reactor, t_g is equal to about 60 μs. In this case the neutron population will increase according to the formula:

$$n(t) = n_o \exp\{((1-\beta)k_{eff} - 1)t / t_g\} = n_o \exp\{((1-\beta)k_{eff} - 1)t \cdot 17\,000 \text{ s}^{-1}\}$$

For such a prompt supercritical reactor, the neutron population, and thus the power level, will increase extremely rapidly, so rapidly in fact that in most cases the reactor will be destroyed. The control systems will simply not be fast enough to stop the run-away chain reaction.

If a reactor is only slightly supercritical, the increase in the power production is slow. The hot fuel will heat the water coolant which in turn will expand and start to boil. The chain reaction will then slow down and ultimately stop since the density of the moderator material (water) is reduced.

In a prompt supercritical reactor, the increase of the power production in the fuel is so fast that a substantial part of the heat produced is used for melting the fuel and the cladding. Heat will of course also be transferred to the water coolant, but this transfer will not be large and fast enough to avoid the melting of the fuel. The melted fuel will flash the water coolant thereby initiating a steam explosion. The fuel disintegrates, water and melted fuel particles are ejected out of the reactor tank, and radioactive materials are scattered over the surrounding area.

From the above considerations, it is seen that in a major, destructive criticality accident, the amount of heat produced must be large enough to melt a major part of the fuel. Actually, even more heat must be produced because some of the heat is transferred to the coolant, and because it takes some time for the steam explosion to disrupt the core so much that the reactor becomes subcritical. During this (admittedly short) period the power production will continue.

The consequences of criticality accidents will be most severe in the case of refuelling or defuelling accidents where the reactor pressure vessel is open, allowing the released radioactive materials to contaminate the surrounding environment.

4.2.2 Destructive experiment and accidents

To gain an idea about the amount of energy that must be produced to cause the destruction of a major part of the reactor core during a criticality accident, one may consider available information on such accidents.

In 1954, the BORAX 1.2 MW_t light-water reactor at the National Reactor Testing Station (NRTS) (now known as Idaho National Engineering and Environmental Laboratory) in Idaho, USA, was intentionally destroyed by a reactivity experiment as the last experiment in a series of safety-related investigations [Dietrich, 1956]. The reactor was equipped with plate-type fuel elements of aluminium containing highly enriched uranium. The total energy released during the excursion was 135 MWs.

From the data given in [Dietrich, 1956] and [IAEA, 1960], the total amount of metal contained in the fuel and its cladding has been calculated to be 85 kg, practically all of which was aluminium. To heat this amount of aluminium from room temperature to the melting point and to then melt it, an energy of 92 MWs is needed. (This figure was obtained using a melting point of aluminium of 660 °C, a specific heat of 1070 J/kg K and a heat of fusion of 400 J/kg.) Thus, in this experiment, the ratio between the total energy release and the amount of heat needed to melt all fuel and cladding was 1.47.

In 1958, the SL-1 nuclear power plant of the US Army, also located at NRTS in Idaho, USA, suffered a criticality accident while there were openings in the reactor tank lid [Joint Committee on Atomic Energy, 1961]. The SL-1 reactor was a 3 MW_t pressurised water reactor. The exact reasons for the accident which killed three reactor operators are not known. Like the BORAX reactor, the SL-1 was provided with plate-type fuel elements of aluminium and highly enriched uranium. Several estimates of the total energy release were made. One based on measurements on a single fuel fragment resulted in a value of 50 MWs. Other estimates based on gaseous activity and on an analogy with SPERT and BORAX experiments suggested a range of 100–500 MWs.

From data given in [IAEA, 1962], the total amount of metal contained in the fuel and its cladding has been calculated to be 259 kg, practically all of which was aluminium. To heat this amount of aluminium from room temperature to the melting point and to then melt it, an energy of 280 MWs is needed. Thus, in this case, the ratio between the total energy release and the amount of heat needed to melt all fuel and cladding was in the range of 0.18–1.79.

The total energy produced during a criticality accident depends not only on how prompt supercritical the reactor becomes, but also on how fast the reactivity is increased, that is, how rapidly the control rods are moved out of the reactor. If the movement is very slow, the increase in the moderator temperature and the boiling of the moderator will be fast enough to compensate, at least partly, for the increased reactivity. In such a case, the damage to the fuel, if any, will be limited, and the same is true for the release of radioactive materials. If, on the other hand, the reactivity increase is very rapid, the melting and destruction of the reactor core is unavoidable. In

Table 4.5. Parameters for the nuclear reactor on board the freighter Sevmorput. *From [Register of Shipping of the USSR].*

Reactor power level	135 MW_t
Number of fuel assemblies	241
Height of reactor core	100 cm
Outer diameter of fuel rods	0.58 cm
Heat transfer area of core	0.26 m^2
Number of fuel rods per assembly	53
Fuel material	U-Zr alloy
Cladding material	Zr alloy
Operating period	app. 10000 eff. hours

the case of the destructive BORAX experiment, the increase of the reactivity was very rapid, probably more so than any reactivity increase in connection with refuelling or defuelling accidents. There are reasons to believe that the reactivity increase was slower and that the ratio between the total energy produced and the amount of heat needed to melt all fuel and cladding was lower for the SL-1 accident than for the BORAX experiment.

The factor of 1.5 which is used below for the ratio between the total energy produced by the accident and the energy needed to melt all fuel and cladding will therefore correspond to a worst-case criticality accident.

4.2.3 Russian naval reactors

Detailed design information on submarine reactors is not available in the open literature. Hence any estimate of the consequences of a destructive criticality accident involving a submarine reactor with an open reactor tank is necessarily based on assumptions. In order to make such estimates, the reactor of the Russian nuclear-powered icebreaking freighter *Sevmorput*, for which some reactor information is available [Register of Shipping of the USSR], was selected as presumably not too different from modern Russian naval reactors. As is true of almost all nuclear submarines, the *Sevmorput* reactor is a pressurised water reactor.

From the data in Table 4.5 it is possible to calculate the total amount of metal, primarily zirconium, in the fuel and cladding. Assuming a density of zirconium of 6.50 g/cm^3, a value of 2200 kg of metal was obtained. To heat this amount of zirconium from room temperature to the melting point (1860 °C) and to then melt it, an energy of 1675 MWs is needed (based on a specific heat of 310 J/kg K and a heat of fusion of 180 J/kg).

Using the value of 1.5 for the ratio between the total energy produced in a destructive criticality accident and the heat energy needed to melt the fuel, a total energy release of about 2500 MWs is then obtained.

Table 4.6. *Fission product release data [ANL, 1963]. Here,* γ *is the cumulative yield (the number of nuclei produced per fission);* f_r *is the fraction of all nuclei of a given kind to be released during the accident; and* λ *is the decay constant. (The* f_r *values are extracted from the discussion in Section 5.1.)*

Nuclide	γ	f_r	λ (s^{-1})
^{90}Sr	0.058	0.02	$7.63 \cdot 10^{-10}$
^{137}Cs	0.0615	0.1	$7.29 \cdot 10^{-10}$

Since one fission corresponds to an energy release of about 200 MeV or $3.2 \cdot 10^{-17}$ MWs, an energy release of 2500 MWs corresponds to

$$N_f = 8 \cdot 10^{19} \text{ fissions/accident}$$

The power level of *Sevmorput*, 135 MW_t, is greater than the 70–90 MW_t reported for first and second generation Russian submarines [Khlopkin *et al.*, 1997]. It may thus be argued that the amount of metal to be melted, and therefore also the energy production, is overestimated. However, it may also be argued that the larger fuel masses involved in submarine reactors as opposed to the small BORAX and SL-1 reactors imply that it takes longer for a submarine reactor to become subcritical since larger masses have to be moved. It could further be argued that the use of the factor 1.5, which was derived for reactors with power levels of around 1 MW_t, is dubious for reactors with power levels of around 100 MW_t. Nevertheless, the results obtained are still believed to be of the right order of magnitude. Assuming an uncertainty of a factor 2, the number of fissions in a worst-case destructive accident should then be in the range

$$N_f = 5\text{–}20 \cdot 10^{19} \text{ fissions/accident}$$

4.2.4 Radionuclide releases

In order to determine the release of radionuclides from a given event, it is necessary to know the cumulative yield γ (the number of nuclei produced per fission), the fraction of all nuclei of a given kind to be released during the accident f_r and the decay constant λ for each of the fission products under consideration. The latter is related to the half-life $T_{½}$ by the relation

$$\lambda = \frac{\ln(2)}{T_{½}} = \frac{0.693}{T_{½}}$$

Values of these parameters for two of the most important fission products are presented in Table 4.6.

4.2.5 Accidents involving cores with spent nuclear fuel

Just before defuelling, the amount of fission products in a reactor core is very large, and in the event of a criticality accident some of these fission products will be released in addition to those produced during the accident.

According to [Register of Shipping of the USSR] the operational period of *Sevmorput*'s core is 10 000 effective hours. This presumably means 10 000 hours or 417 days at full power. Since the power level is 135 MW_t, the core will then have produced about $4.9 \cdot 10^9$ MWs at shut-down. This requires about $1.5 \cdot 10^{26}$ fissions.

Assuming that the average time between each refuelling of a submarine is 13 years (see Section 4.2.6), the average fission rate in the reactor becomes

$$n_f = 3.7 \cdot 10^{17} \text{ fissions/s}$$

and the production rate of one particular fission product is γn_f. The fission products will not only be produced, but they will also decay. The decay rate is equal to λN where N is the number of nuclei of the fission product considered. From this information, the activity A_{fp} of a given fission product may be calculated after a reactor operational period T followed by a cooling period τ before the accident:

$$A_{fp} = \gamma\, n_f\, (1 - e^{-\lambda T})\, e^{-\lambda \tau}$$

The activity released due to the accident is obtained by multiplying A_{fp} with f_r. The following values of the released activities for the two fission products listed in Table 4.6 are then obtained:

^{90}Sr:	100 TBq
^{137}Cs:	600 TBq

These figures refer to the activity just after the accident. (If instead the calculations had been based on the inventory in Appendix A in combination with f_r from Table 4.6, the resulting activities would have been about 70 TBq for ^{90}Sr and about 350 TBq for ^{137}Cs. This illustrates the uncertainties inherent in this kind of calculations.) The fission products will decay exponentially with time after the accident. However, due to the long half-lives of ^{90}Sr and ^{137}Cs, the activities of these two radionuclides are not significantly affected by the length of the operation and the cooling time. The figures given above include the activity produced during the accident which is negligible anyway compared to the activity generated before the accident.

The amount of radioactivity released is much higher in an accident involving spent fuel than in one involving new fuel. This is hardly surprising considering the large accumulation of long-lived fission products during the operational period. Consequently, the risk of significant contamination of a large area is much larger in the case of spent fuel.

It may be argued that k_{eff} is usually smaller in the case of a burned core since this is the reason for refuelling, and that the risk of a serious criticality accident should therefore be smaller. However, even at the end of its life, a (cold) core must have a k_{eff} large enough to overcome the higher temperature during operation as well as the xenon poisoning (a build-up of neutron-absorbing ^{135}Xe which has a half-life of 9.14 h). Hence even a burned core may become prompt supercritical if the control rods are removed.

In the discussion above it is assumed that the time between each refuelling is 13 years, and that the operational time at full power is 417 days or 1.14 years. From these two figures one obtains a full-power utilisation of a submarine reactor of about 9%. Since a submarine is hardly running at full power all the time, the fraction of the time it has been at sea is presumably around 15–20 %, which seems to be a reasonable estimate.

4.2.6 Risk estimate of criticality accidents

If all safety regulations are strictly followed, criticality accidents should not occur. Yet, in the past they have nevertheless occurred.

The most serious accident occurred in 1985 at Chazhma Bay near Vladivostok during the completion of refuelling work on the Project 675/Echo-II class nuclear submarine *K-431*. The reactor in question had been refuelled and the reactor vessel closed, but the gasket of the lid leaked so that the lid had to be removed again. During this process, the control rods were not properly detached, and as a consequence they were lifted out of the core with the lid. This led to an uncontrolled chain reaction with two power excursions in the reactor and a subsequent fire in the reactor compartment. Ten persons died as a result of the accident, and many received high radiation doses [Yablokov *et al.*, 1993; Ølgaard, 1996a; Soyfer *et al.*, 1995].

In 1980 a criticality accident occurred at Severodvinsk in one of the reactors of a submarine that was undergoing maintenance work. Power was supplied to the control rod system and the rods started to move out while the safety system was not functional due to lack of power. The accident damaged the reactor core and the primary circuit, but there were no casualties. Presumably the reactor tank was not open, and consequently the release of radioactive materials to the environment must have been quite limited [Osipenko *et al.*, 1992; Ølgaard, 1996a].

A criticality accident reportedly occurred in 1970 in a nuclear submarine under construction at the "Krasnoye Sormovo" shipyard in Gorki (now Nizhniy Novgorod). Hydraulic tests of the primary circuit were performed. However, the control rods had not been sufficiently affixed, and high velocity coolant lifted the rods out of the core causing the reactor to go critical. The criticality resulted in a fire and the release of radioactivity. Due to the limited information available it is not possible to assess the causes and magnitude of this accident [Ølgaard, 1996a].

In 1968 a Project 667/Yankee class submarine suffered a criticality accident during maintenance work at Severodvinsk. One of the reactors went critical when the control rods moved out of the core due to the erroneous connection of some electric cables. The fuel and the reactor tank had to be replaced. Presumably the reactor tank was closed when the accident occurred. There were no casualties [Osipenko *et al.*, 1992; Ølgaard, 1996a].

In 1965 a criticality accident occurred during refuelling of a submarine at Severodvinsk. The reactor went critical due to the carelessness of the crew. Radioactivity was released from the submarine, and some of the personnel were exposed to radiation. No information is available on casualties. There may also have been a fire. The reactor had to be replaced. In this case the reactor tank was clearly open [Osipenko *et al.*, 1992; Ølgaard, 1996a].

Of the five criticality accidents discussed above, two involved refuelling, and these accidents led to the release of radioactivity and irradiation of personnel due to an open reactor tank. One of the refuelling accidents was very serious, costing the lives of ten crew members.

It should be noted that none of the reported criticality accidents involved decommissioned, non-defuelled submarines.

It is possible to roughly estimate the probability of a refuelling accident on the basis of available data. According to [Yablokov *et al.*, 1993], the Russian Navy in the early 1990s needed to refuel about 20 ship reactors per year. At that time about 150 Russian nuclear-powered naval vessels were in operation [Ølgaard, 1993]. These ships contained an estimated 260 reactors [Yablokov *et al.*, 1993]. This implies that the average time between each refuelling is about

$$260 \text{ reactors}/20 \text{ reactors per year} = 13 \text{ years}$$

Russian ship reactors had at that time accumulated a total of about 7700 ship reactor years (sry) [Ølgaard, 1994], so that the number of refuellings that had been performed must have been on the order of

$$7700 \text{ sry}/13 \text{ sry per refuelling} = 600 \text{ refuellings}$$

These 600 refuellings resulted in two refuelling accidents, of which at least one was serious. Thus, the probability of a serious refuelling accident in the Russian Navy is about

$$1/600 \text{ refuellings} = 2\cdot10^{-3} \text{ per refuelling}$$

4.2.7 Precautionary measures against criticality accidents

As already mentioned in Section 2.4.4.1, a number of precautionary measures have been introduced in Russia to ensure nuclear safety [Khlopkin *et al.*, 1997]. This is discussed in this section from the point of view of prevention of criticality accidents during defuelling.

Decommissioned, non-defuelled submarines in long-term storage have a 1-m long piece removed from all cables to the control rod drive mechanisms, and the cable ends are insulated. The gears of the control rod drive mechanisms are blocked by welding and the use of stoppers. The electricity supply to the main control room is interrupted. This should ensure that while the submarines are in long-term storage their reactors cannot go critical.

More recently, it has been suggested to remove the water moderator from the reactor vessel just prior to the reactor defuelling. This would ensure that even if all control rods were removed from the reactor, it would still not go critical. The draining of the reactor tank is verified by inserting a suction tube into the reactor through a control-rod guide tube. Draining of the secondary and tertiary circuits is performed and checked, and pipelines connecting these circuits are dismantled.

Since the defuelling of nuclear submarines in long-term floating storage does not occur until several years after reactor shut-down (giving the reactor ample time to cool down), there is no risk of a loss-of-cooling accident when the reactor vessel is drained.

Other measures to prevent criticality accidents during defuelling are the use of neutron detectors (for example, coupled to a loudspeaker) to detect an enhanced neutron level, as well as the use of soluble poison in the moderator. In Russia soluble poison in the moderator is not used, partly to simplify waste handling, and partly because it is difficult to obtain the same poison concentration throughout the primary system. It is not known whether neutron detectors are used during defuelling.

Criticality accidents should not occur and will not occur if the above rules and procedures are followed. However, they have nevertheless occurred and may occur again in the future. One possible cause of a criticality accident during defuelling would be that the reactor vessel had not been sufficiently drained and the suction tube which was inserted to control the water level did not work for some reason. The control rods would then be lifted up together with the reactor lid, and the reactor would go supercritical.

4.2.8 Some remarks on criticality accidents

It should be emphasised that there is significant uncertainty concerning the figures derived in Section 4.2. However, the authors believe that the estimates presented are of the right order of magnitude.

This section did not consider important questions such as the size of the contaminated area around the accident site or the intensity of the contamination. These parameters of course strongly depend on the detailed evolution of each accident, as well as the weather at the time and other site-specific conditions.

5 DISPERSION OF RADIONUCLIDES

The cross-border consequences of an accident that involves a release of radionuclides are determined by the distribution of these radionuclides in the environment. A release from a hypothetical accident on board a decommissioned, non-defuelled nuclear submarine will necessarily take place either directly to the sea or to the air. Both cases are studied in this chapter.

As mentioned in Section 2.3.2 and Section 2.4.2, some 50–70 such submarines equipped with one or two pressurised water reactors, each reportedly with a thermal power of between 70 MW_t and 90 MW_t, were moored at various naval bases in Northwest Russia in 1995. More submarines are scheduled to join them in the years to come. As some of them are moored less than 100 km away from international borders, these submarines may pose a potential hazard to neighbouring countries.

In quantitative risk analyses, risk is generally defined as the product of likelihood and consequence. All elements relevant to such a study are taken into account in a probabilistic manner. Parameter values are often derived from statistical data, for instance the probability of a pipeline burst or a traffic accident. In the case of non-defuelled, decommissioned nuclear submarines, however, reliable data are scarce due to the limited number of such accidents so far as well as the secrecy inherent in defence-related activities.

Based on a historic investigation of reported accidents with nuclear submarines, the probability of a *refuelling* accident was estimated to be on the order of 10^{-3} per refuelling [Ølgaard, 1996a]. Russian scientists estimate the probability of simultaneously having water in the core and suffering from a catastrophic displacement of absorber rods to be on the order of 10^{-7} [Khlopkin *et al.*, 1997]. This figure is, however, primarily based on expert judgement, and bears a large uncertainty. It is therefore concluded that provided all safety precautions are adhered to, the likelihood of a criticality accident during defuelling is low; however, because of the large uncertainty in the estimated likelihood, it is meaningless to carry out a complete risk analysis. The evaluation below is therefore limited to a *consequence* analysis: only the radiological consequences of a potential release of radioactivity into the air following a criticality accident are considered. Due to the cross-border nature of the study, emphasis is on the possible dispersion of radionuclides and the subsequent exposure of the public to ionising radiation over intermediate to long distances (100–400 km). Within close vicinity of an accident, where the immediate consequences are likely to be more severe, the situation is primarily a matter of national interest and is therefore only briefly touched upon here.

The following elements are important in order to estimate the radiological consequences of a release following an accident with a decommissioned nuclear submarine:
(1) The nuclear inventory of the reactor under consideration. This depends on the type of reactor, its power, its total run time and the time elapsed since shut-down.
(2) The fraction of the core inventory that will be released into the environment. This release fraction depends among other things on the extent of core damage, the presence of a containment and the volatility of the various chemical elements.
(3) The dispersion of radionuclides into the environment and the various pathways of exposure. The actual dispersion depends strongly on the chemical and physical properties

of the materials released, the effective release height, the meteorological circumstances during the event and the local terrain.

(4) The radiological effect of the various radionuclides. This effect differs for the various exposure pathways.

(5) The characteristics of the population(s) being exposed, for example, general behaviour and diet.

When evaluating the possible consequences of a potential accident, many parameters are necessarily unspecified. In some cases, however, one can derive typical values which will be sufficient for the moment. The influence of other elements on the process (for example, dispersion and ingestion) is illustrated by different calculations.

5.1 Source term

A nuclear reactor contains an extensive list of radionuclides, and the composition changes with increasing run time. Most important are the build-up of fission products such as ^{137}Cs and the presence of actinides such as ^{238}Pu. After shutdown, the radionuclide inventory will continue to change due to radioactive ingrowth and decay. Detailed information about naval reactors is unavailable, but as mentioned earlier, for the purpose of this study the reactor of the nuclear freighter/icebreaker *Sevmorput* is considered representative [Register of Shipping of the USSR]. The calculations presented below are therefore based on the *Sevmorput* reactor inventory; they assume a total operation time of 1.25 years at 67.5 MW_t, and that the reactor has been shut down for five years (see Section A.2 of Appendix A). Compared to other parameters yet to be discussed, the uncertainty in the core inventory is relatively small.

The long list of potentially hazardous radionuclides can be shortened considerably by taking into account the activity present in the core at the time of the accident, the release fraction for each radionuclide and radiological effects for a number of pathways, thereby leaving only a small number of relevant radionuclides. However, estimating the release fraction (f_r in Chapter 4) is not an easy task. A criticality accident with a decommissioned naval reactor may involve 10^{19}–10^{20} fissions, equivalent to a sudden energy release of about 1 GJ [Ølgaard, 1997]. Most of this energy will be used to heat, melt, vaporise and/or mechanically destroy material inside the reactor core, including the fuel. Due to the resulting steam explosion, part of the nuclear inventory will be discharged into the surrounding environment. Many studies have assessed the release fraction of the various radionuclides in a nuclear accident. Values for severe core accidents involving nuclear power stations typically range from about 0.001 for actinides (such as Pu and Am) and other non-volatile elements to 1.0 for noble gases (such as Kr and Xe). Table 5.1 shows two sets of parameter values, one of them based on a noteworthy safety study carried out in the mid-1970s known as WASH-1400 [NRC, 1975] while the other is based on a recent evaluation of the Chernobyl accident [NEA, 1995]. Note that both parameter sets agree fairly well apart from the relatively large release fraction for actinides in the case of Chernobyl; the disagreement is attributed to the burning of graphite for more than a week.

Table 5.1. Element-specific release fractions of various radionuclides into the surrounding environment for severe reactor accidents. The data sets are further described in the text. The rightmost column (f_r) *shows the values used in this study.*

Radionuclides	[NRC, 1975]	[NEA, 1995]	[Khlopkin *et al.*, 1997]	f_r
Kr, Xe	0.9	1.0	0.1	0.3
I	0.7	0.5–0.6	0.01	0.2
Cs, Rb	0.4–0.5	0.2–0.4	0.01	0.1
Te, Sb	0.3–0.4	0.25–0.6	0.01	0.1
Sr, Ba	0.05–0.06	0.04–0.06	0.002	0.02
Ru, Mo, Rh, Tc, Pd, Co	0.02–0.4	> 0.035	0.002	0.02
Pu, Am, Np, Cm, Zr, Y, Ce, Pr, Nb	0.003–0.004	0.035	0.002	0.002

All available studies of release fractions refer to situations which differ considerably from a criticality accident involving a decommissioned naval reactor. There are valid arguments for the presumption that release fractions in the case of a criticality flash with a naval reactor are smaller than those given above. On the other hand, in the case of a nuclear submarine defuelling accident, there is virtually no containment. Release fractions proposed by the Kurchatov Institute are much smaller, especially for the more volatile elements such as caesium (about a factor of 40 lower) and iodine (a factor of 60), but these values are only briefly discussed [Khlopkin *et al.*, 1997]. Unfortunately, values based on extended safety studies or accident evaluations applicable to the case studied here are lacking, so release fractions have had to be estimated. Due to the large uncertainty in these parameters, conservative estimates, that is, the upper limit of still credible values, have been applied. Noting that on average about 25% of the Chernobyl releases were discharged during the first day of the accident [UNSCEAR, 1988; NEA, 1995], rounded values were set at approximately 25–30 % of the typical literature values for severe core accidents involving nuclear power plants (see Table 5.1, rightmost column).

A ranking of the relative importance of the radionuclides present in the source term was derived based on the core inventory, the release fractions given above and a first-order assessment of the radiological burden for the exposure pathways of external radiation, inhalation and ingestion. During a criticality flash, many very short-lived radionuclides are formed. They dominate the radiation level shortly after the accident, and their impact may be of great importance in the vicinity of the accident site. They are of no concern with respect to cross-border radiological contamination, however. In the source-term reduction calculations, radionuclides with half-lives shorter than a few minutes were therefore omitted, and the following radionuclides (and decay products, when applicable) were identified as the cause of the major part of the radiation dose: ^{137}Cs/^{137m}Ba, ^{134}Cs, ^{90}Sr/^{90}Y and, to a much lesser extent, ^{132}Te/^{132}I, ^{133}I and ^{135}I.

Table 5.2. Relative dose contributions for selected pathways of the most important radionuclides present in the source term. "Ground shine" is external radiation from radionuclides deposited on the ground and on surfaces, while "cloud shine" is external radiation from the radioactive cloud. An asterisk indicates that the dose from decay products is included in the relative dose estimate. Relative dose contributions for ingestion depend heavily on specific consumption patterns, and are therefore not quantified.

Inhalation		Ground shine		Cloud shine		Ingestion
Nuclide	Relative dose (%)	Nuclide	Relative dose (%)	Nuclide	Relative dose (%)	Nuclide
^{137}Cs*	53	^{137}Cs*	78	^{137}Cs*	75	^{137}Cs*
^{90}Sr*	43	^{134}Cs	14	^{134}Cs	14	^{134}Cs
^{134}Cs	2	^{132}Te*	3	^{132}Te*	3	^{90}Sr*
		^{135}I	2	^{135}I	3	
		^{133}I	2	^{133}I	2	

Table 5.2 ranks the most important radionuclides for each selected pathway, radionuclides that are responsible for at least 95% of the total effective radiation dose in each case. Dose-conversion coefficients for external radiation were taken from [Kocher and Sjoreen, 1985] or computed using the computer code SOIL_RAD [Blaauboer, 1995], while those for inhalation and ingestion were taken from [IAEA, 1996]. Based on this initial analysis, the following *reduced source term* was derived for use in subsequent dispersion and dose calculations:

^{137}Cs: 350 TBq
^{134}Cs: 35 TBq
^{90}Sr: 70 TBq

Of these radionuclides, ^{137}Cs is by far the most dominant, in the short term as well as the long term. Note that this source term is two to three orders of magnitude lower than that of the 1986 Chernobyl accident [NEA, 1995].

5.2 Release to the sea

Although the risk of a serious accident occurring to moored, non-defuelled, decommissioned submarines is slight, it is useful to discuss the consequences and hazards to the marine environment should one of these vessels sink at her moorings and thereby release radioactivity to the sea. As may be seen in Table 2.4, there were a total of 52 laid-up non-defuelled, decommissioned submarines at the Northern Fleet in September 1995. By their very nature, submarines are robust; nevertheless, after long periods of time in the sea without constant maintenance, hull fittings, valves, hatch closures and other components can corrode, allowing the vessel to flood and sink.

[Khlopkin *et al.*, 1997] stated that two nuclear submarines (of the Pacific Fleet) have sunk at their piers. One of the two was laid-up. Based on this, the probability of a moored, decommissioned submarine sinking and water penetrating the reactor compartment has been estimated to be $1.5 \cdot 10^{-5}$ per year [Khlopkin *et al.*, 1997].

Even though the sinking of a defuelled, decommissioned submarine would be a setback to the whole decommissioning programme, the consequences would not necessarily be severe. Reactor pressure vessels and the primary pipework are designed to withstand considerable pressures and would not leak fuel or fission products into the sea. The only contamination would come from corrosion of the outer surfaces of the power plant. Recovery of the submarine would present few difficulties. This scenario is discussed in Section 5.2.1.

The consequences might be more serious if a passing ship hit the moored submarine. Again, sinking by collision would be expected to be a very rare event although such an incident involving a defuelled submarine from the Pacific Fleet was recently reported at Kamchatka [Handler, 1998]. After the collision, the reactor compartment may be breached and the primary circuit broken. In this case, the interior of the reactor would be exposed to the sea, and corrosion of the fuel could begin very quickly, releasing fission products and fuel to the marine environment. This is illustrated in Section 5.2.2.

The remaining possibility is the hypothetical criticality incident during defuelling, followed by the sinking of the vessel. A brief discussion of this scenario is presented in Section 5.2.3.

5.2.1 Sinking of an undamaged submarine

Table 2.4 and Figure 2.3 show that the decommissioned submarines are located at nine bases in Northwest Russia. In this case study, the Ara Bay site was chosen for the analysis of a marine release incident. As of 1995, six decommissioned and non-defuelled submarines were in floating storage there.

There has been a reported nuclear incident in the Ara Bay [Ølgaard, 1996a; Nilsen and Bøhmer, 1994]. In 1989, 74 TBq of liquid radioactive waste were discharged to the bay following the return of the Project 675/Echo-II class submarine *K-131* that had developed a fault in the reactor, giving rise to a leak of contaminated primary coolant.

Using the methods developed by the Source Term Working group of the IAEA International Arctic Seas Assessment Project (IASAP) [IAEA, 1997a], a prediction can be made of the radioactivity and the hazards which might result from a sunken but undamaged submarine.

As shown in Figure 5.1, the Ara Bay is an inlet running north to south just to the west of Ura Bay (another submarine mooring location) and 28 km west of the Murmansk Inlet (Kolskiy Zaliv). The Ara Bay is 11 km long with a mouth 3 km wide, opening out into the Motovskiy Zaliv, a large bay running west to east in the southern Barents Sea. The availability of hydrographic details of the bay is limited, but it has a depth of 90 m at the mouth for tidal interchange, shallowing to 10–15 m at the southern end. With no major rivers, freshwater input to the bay will be limited and suspended sediment levels low.

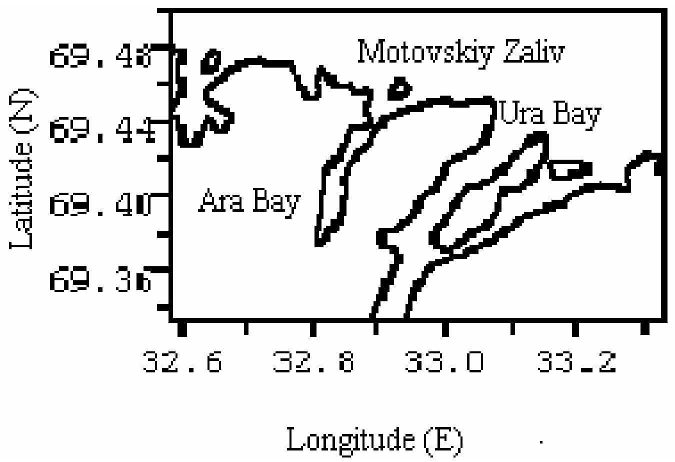

Figure 5.1. Map showing the location of the Ara Bay on the Kola Peninsula.

If a submarine sinks in these shallow waters, it is unlikely that there will be any damage to the power plant and its primary systems causing a leakage. The only release of radioactivity will come from corrosion of the activated steel from the outside surface of the reactor pressure vessel itself. Other sources of radioactive contamination might be found in storage tanks in the reactor compartment, but these are drained as part of the storage afloat decommissioning procedures [Khlopkin *et al.*, 1997].

In the IASAP study, the activity in the pressure vessel steel was assumed to be 10% of all the activated material. Using the information from the dumped *Lenin* reactor as a basis [IAEA, 1997a], the IASAP program was run to establish the leakage rates for the major activation isotopes ^{60}Co, ^{59}Ni, ^{63}Ni and ^{14}C. The activation inventory assumes the submarine was taken out of service in 1980 and sinks in the year 2000. From a modelling point of view, it also assumes that there is a free flow of water in and out of the reactor compartment. This latter assumption is of course very conservative.

Figure 5.2 shows the release rates for the four isotopes over the period 2000 to 2020. A total of about 300 MBq will be released by corrosion from the walls of the two pressure vessels in the first year submerged, dropping to an estimated 180 MBq per year by 2020. The ^{60}Co contribution is dropping steadily, and the ^{63}Ni release fraction dominates the period.

These elements will not stay in suspension or in the dissolved state for long. Three of the four isotopes have a K_d value of about 1.0–2.0·10^5 m^3/tonne for coastal sediments [IAEA, 1985]. ^{14}C is two orders of magnitude lower at 2.0·10^3 m^3/tonne, but all the figures imply a strong affinity for adsorption onto coastal sediments. This means that the isotopes will most likely bind to the sediments and deposit on the bay floor. They may of course also just fall to the bottom of the reactor compartment with the other rusting debris and not leave the hull at all.

Given the lack of detailed hydrographic knowledge of the Ara Bay and its circulation, it was only possible to construct a generic model to give an order of magnitude estimate of the mixing and dispersion of released activity within the bay. The ECOS II estuarine simulation

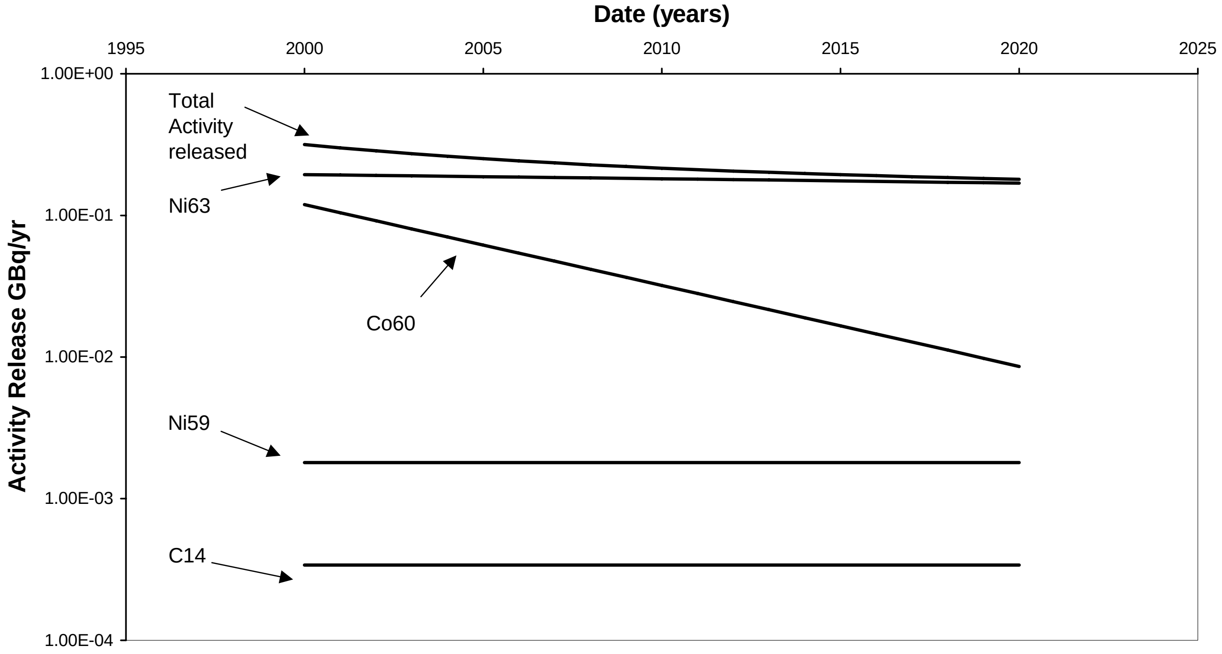

Figure 5.2. Activity released from reactor pressure vessels in an undamaged sunken submarine at the Ara Bay based on the IASAP study [IAEA, 1997a].

shell developed by Plymouth Marine Laboratory [Harris *et al.*, 1993] was used to model the processes. The shape of the estuary and bottom topography served as input to the model. Salinity and suspended sediment data were estimated or derived from various sources including [Ali *et al.*, 1997b] and [Owrid and Collins, 1990]. Freshwater flow into the end of the bay was estimated at 1 m^3/s. Tidal information was taken from the Admiralty tidal predictions for Murmansk [HMSO, 1997]. A release point was chosen 1 km from the end of the bay; this is 10 km from the open sea.

Running this simulation for a 100-day period showed that only very small radionuclide concentrations were to be found in the bay. Very little went beyond 1.5 km north of the release site. As expected, the bottom sediments accumulated activity, while the suspended and dissolved activity in the water column was less than 0.1 Bq/m^3. Based on the ^{60}Co isotope and dose data from [Kocher, 1983], this would lead to a dose rate of about 0.4 μSv per year for someone in a small craft in the harbour.

This is a vanishingly low figure, especially bearing in mind the initial assumption that the reactor compartment was free flushing. It is most unlikely that this would be the case but trying to predict the number and size of reactor compartment penetrations could be difficult. This would suggest that lifting the submarine and restoring watertight integrity should not represent a problem to salvage personnel.

5.2.2 Sinking of a damaged submarine

Despite the very low frequency postulated for ship collision events, such an accident could conceivably damage the primary circuit of a submarine and sink the vessel. Provided the water was deep enough under her keel to allow the vessel to submerge below the level of the

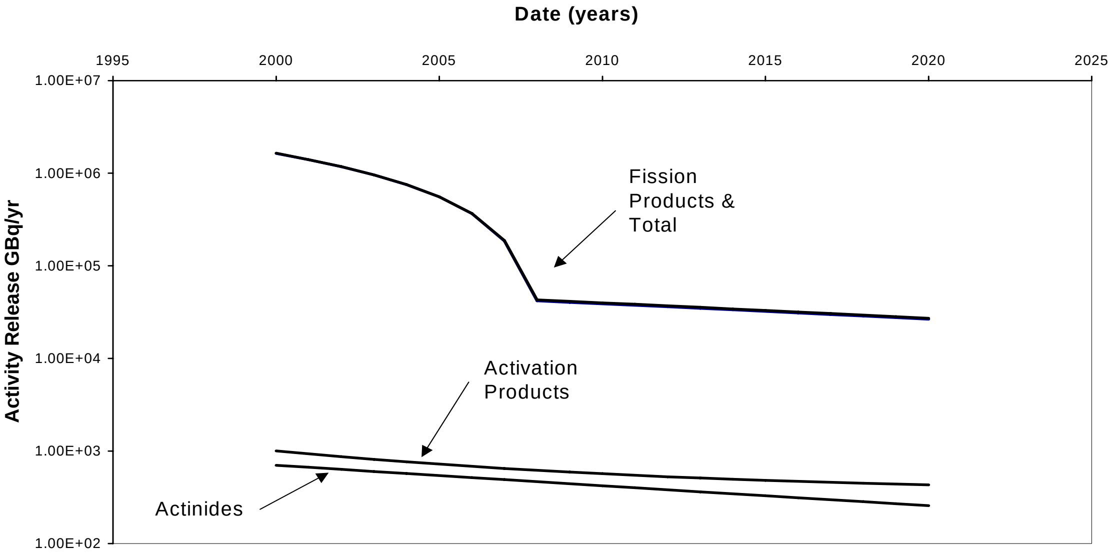

Figure 5.3. Activity released from reactor pressure vessels in a collision-damaged sunken submarine at the Ara Bay based on the IASAP study [IAEA, 1997a].

breaks, this would expose the fuel and the highly active steels in the core of the pressure vessel to seawater corrosion. The IASAP Source Term Working Group considered such a possibility for the reactors dumped in the Kara Sea, and this release rate model has been applied to the Ara Bay scenario.

It is assumed that the collision and sinking opens the reactor compartment and the primary pipework of one reactor only. This would be a reasonable assumption; however, whether the fuel cladding will present a barrier to fuel corrosion and release of fission products is uncertain. In this simulation, it was assumed that the cladding barrier was broken, and that seawater thus could penetrate and corrode the fuel. Again, it was assumed that the submarine was taken out of service in 1980 and sinks in the year 2000.

Using the dominant isotopes of the fission product and actinide inventory of Appendix A.1 and the activation product inventory used in Section 5.2.1, the IASAP model was run to determine release rates. The results for the total of the fission products, the activation products, the actinides and the total of all activity release rates are shown in Figure 5.3.

In the year of the collision, an estimated 1.6 PBq of total activity is released to the Ara Bay. With the actinide and activation products contributing only 1 TBq, the fission products dominate the release. By the year 2008, the more mobile fission products have leached from the fuel; the release rate is still dominated by fission products, but now the less mobile fraction predominates.

In the first year, ^{137m}Ba is the most important isotope as a water-borne health hazard. 0.5 PBq is released, and this was used in the ECOS II simulation.

The results of this scenario from ECOS II were similar to the previous case in that the activity did not tend to move far down the bay; the geographic spread was similar. A rise in the bottom topography towards the mouth will also help to trap the activity bound to bottom sediments within the confines of the bay.

The dose to the same individual on a small craft in the harbour was higher, a peak of 50 μSv/h from ^{137m}Ba. When all the other isotopes are added in, the total comes to about 100 μSv/h. At 2 km north of the site, average dose rates from the water surface to personnel in a small craft had dropped to about 10 μSv/h. By the mouth of the Ara Bay, the level had dropped to an estimated 1 μSv/h.

It must be stressed that the above is only a rough estimate of the hazard. The assumption of no fuel cladding as a barrier to corrosion release is very pessimistic. If only a fraction of the cladding has been damaged in the impact, the estimated dose levels will drop proportionally. The model is also sensitive to some of the input parameters. If, for example, more sediment was present in the water column from river and stream input than was used in the model, more activity is carried northward to the mouth of the bay.

The dose rate at the water surface around the submarine would be appreciably lower if wind shear across the surface of the bay increased the mixing and dispersion. With a prevailing southwest wind, activity would be washed ashore to the east, to be taken up by beach sediments. Conversely, the dose rate would be higher if there was enough decay heat left in the core to convect the dissolved material to the sea surface above the sunken vessel.

ECOS II does not model radioactive uptake by edible fish species. However, [Khlopkin *et al.*, 1997] proposed a plume model for the spread of activity flushed from an exposed submarine core and demonstrated that fish swimming in this plume did not accumulate enough activity to ban their consumption, if caught a year after the accident.

5.2.3 Criticality accident and sinking

Criticality accidents during refuelling were discussed in Section 4.2. As the atmospheric transport component of such an incident may present a cross-border problem, it is analysed in detail in Section 5.3 of this chapter. The probability of such an event is low, but if it occurred, the quantity of radioactive material that would end up in the sea, deposited from the airborne cloud, is unknown. It would depend on the prevailing wind, rainfall and in the long term, river transport from the land. It is also likely that some of the debris following the release will fall back into the sea around the submarine hull.

The submarine might sink, exposing the interior of the reactor to seawater corrosion as discussed in the previous case, but this time, it is more likely that the cladding protection around the fuel would be lost. In this case, release rates would be higher than given in Section 5.2.2; with the top of the reactor removed, flushing of the core would be enhanced.

5.2.4 Summary of the consequences of marine dispersion

Although the probability of an accident involving a release of radioactivity to the sea at the bases holding non-defuelled, decommissioned submarines is low, a first analysis shows that the hazards following a sinking are also very low. Only if the reactor's primary circuit were broken would the sunken vessel present a problem to site workers and salvage teams. The marine hazards from a criticality incident are difficult to predict but the local consequences would be severe.

From the model, it would appear that little of the released activity would leave the Ara Bay; if recovery were within a year, the release to the Arctic Ocean would be negligible although this statement will require quantification. Much more detail on the hydrology of the Ara Bay would be needed to construct a more accurate model to calculate the leakage of radionuclides into the Barents Sea and Arctic Ocean.

5.3 Release to the air

Because of the cross-border nature of this entire case study, the discussion below focuses on dispersion of radioactivity over intermediate to long distances. The immediate consequences are likely to be more severe near the accident site, but this is primarily a matter of national interest.

A severe defuelling accident with a decommissioned nuclear submarine is likely to give rise to a steam explosion followed by an atmospheric release of radioactive material consisting of gases, aerosols and finely fragmented nuclear fuel. The heat generated during the explosion will cause an initial plume rise. In general, the effective release height is of great importance for the modelling of air dispersion. An effective release height exceeding the so-called *mixing height* (typically 100–2000 m, depending on atmospheric stability) will result in a wider dispersion with less deposition on the local and mesoscale ranges, but most likely this is not the case here. Assuming an energy release of about 1 GJ, the effective release height can be estimated to be in the range of 50–100 m. This result is based on an interpolation between a value of 25 m obtained from the 1954 BORAX experiment in which a very small reactor (1.2 MW_t) was deliberately destroyed [Griffiths *et al.*, 1956], and comparison with the value for a chemical explosion releasing 1 GJ of energy. For values below the mixing height, the effective release height is a less sensitive parameter [Bergman *et al.*, 1997]. Consequently, an effective release height of 75 m was used in the calculations quoted below. Note that this release height is considerably smaller than the values of 200–1200 m found in the case of the Chernobyl accident, during which the plume rise was greatly enhanced due to an enduring graphite fire [UNSCEAR, 1988].

The dispersion and deposition of radioactivity in the environment depends among other things on the chemical and physical properties of the material released [Seinfeld, 1985; Chamberlain, 1991]. With the exception of noble gases (Xe, Kr) and iodine isotopes (the latter present in either gaseous, organically bound and/or particulate form), most radionuclides in the source term (cf. Table 5.1) will be attached to aerosols. This includes the very important caesium isotopes. Many studies have been carried out to determine particle size distributions of radioactive aerosols. Activity median aerodynamic diameters (AMADs) for fallout from nuclear accidents are typically in the range of 0.3–5 μm. For ^{137}Cs from the Chernobyl accident, a median AMAD of 0.64 μm was derived [Dorrian, 1997]. For particle diameters in this range, deposition is relatively low. Both smaller and larger particles tend to deposit more effectively, the former due to Brownian motion and the latter due to gravitational settling [Seinfeld, 1985; IAEA, 1994a]. Aerosol activity size distributions were generally monitored at intermediate to large distances from the source. The above-mentioned values may therefore partly be the result of this selection process. In other words, there is an uncertainty in the particle size distribution immediately after the excursion, that is, in the vicinity of the source. In the dispersion modelling (yet to be described) parameters defining the aerosol properties were nevertheless set according to the above information. This may slightly underestimate the deposition of radioactivity near the source and slightly overestimate the deposition at intermediate to long distances; however, this uncertainty is hardly relevant compared to other uncertainties in the modelling.

Similar to other pollutants, airborne radioactivity emerging from a nuclear accident is subject to the following basic atmospheric processes: (non-linear) horizontal transport and dispersion, vertical mixing, dry deposition and wet deposition. These processes may be characterised by parameters such as wind speed, wind direction, stability class, mixing height, surface roughness and aerosol distribution. The outcome of a real event depends strongly on actual weather and terrain conditions in the source and receptor area. A modelling result for a release at an arbitrarily chosen time for a slightly different source term was already presented in the first phase of the Pilot Study [Smetsers *et al.*, 1994; NATO, 1995a].

In order to make dose estimates, the variability in weather parameters must be considered. For a postulated accident, however, many parameters are not specified. To better illustrate this problem, model calculations were carried out using two different approaches. One approach involved a *probabilistic treatment* of the problem, that is, a weighted average of all possible situations was generated using a statistical database for short-term weather conditions derived from a long series of actual meteorological observations. In the other, more deterministic approach, “real-time” calculations were carried out for a particular set of *hypothetical weather conditions*, in this case yielding more unfavourable results for parts of Northeastern Norway. In both cases, the source was located at Ara Bay, some 100 km away from the Norwegian border, where about six non-defuelled submarines are moored at present (cf. Chapter 2). The results may be considered representative for events taking place not only at Ara Bay, but also at five other nearby sites (Zapadnaya Litsa Bay, Ura Bay, Saida Bay, Olenia Bay and Polyarny). Half of the 52 decommissioned submarines that were reported by [Kværner, 1996] to await defuelling in 1995 were moored in this area.

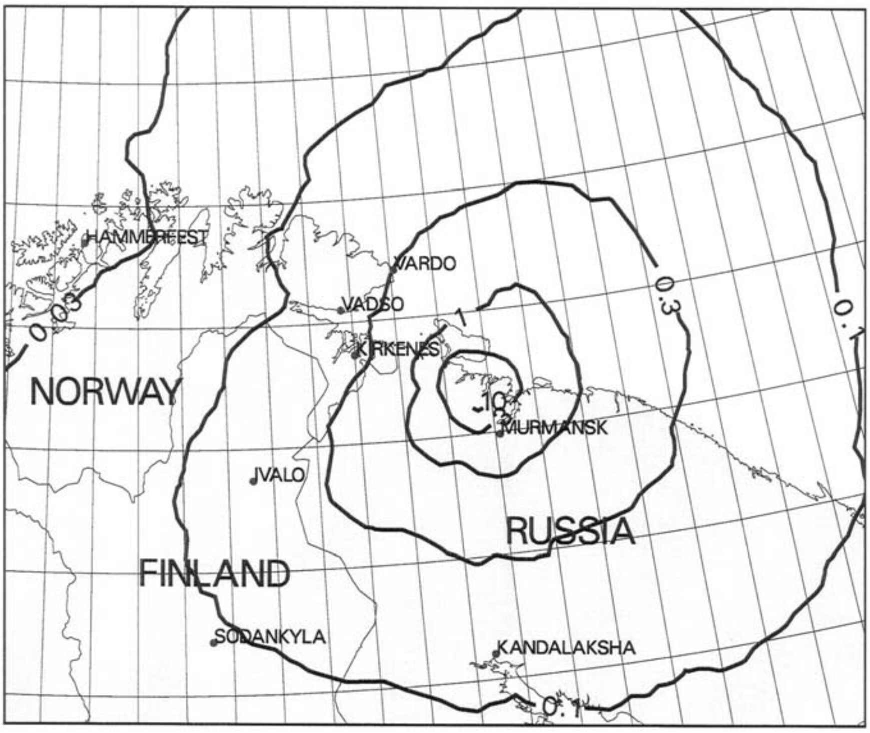

Figure 5.4. Probabilistic deposition contours (kBq/m^2) for ^{137}Cs for a 350 TBq release at Ara Bay. The map shows the calculated average ^{137}Cs deposition for all weather conditions, weighted by their relative frequency of occurrence.

5.3.1 The probabilistic approach

Probabilistic patterns of ground deposition and (integrated) air activity concentrations were calculated using the computer code OPS [van Jaarsveld, 1990; van Jaarsveld, 1995]. This atmospheric transport model, which has been validated on many occasions for regular long-term releases of various air pollutants, computes the transport and deposition of air contaminants for a large number of typical weather situations and subsequently sums the results weighted by their relative frequency of occurrence. Weather statistics were derived from an annual series of short-term meteorological data collected in the Murmansk area throughout 1990. Both dry and wet deposition were taken into account. Aerosols were categorised into several classes: 70% of the airborne radioactivity was attributed to the size category of less than 0.95 μm and 20% to the range 0.95–4 μm; the remaining 10% was attributed to larger particles which deposits more rapidly by sedimentation. Calculations were made on a 15×15 km^2 grid covering an area of approximately 1000×1000 km^2.

Figure 5.4 shows the results for the deposition of ^{137}Cs. Patterns for ^{134}Cs and ^{90}Sr are found by taking into account their relative occurrence in the source term. It is again emphasised that this deposition pattern will never be observed as a result of a real accident, as it is the *weighted average of all possible patterns* that may follow an accidental release. However, it does give a reasonable understanding of the magnitude of the total area affected and the levels of surface contamination that may be expected. Moreover, it indicates areas where deposition is more or less likely to occur. One finds that there is a probability of about 50% that (most of) the fallout will end up in the sea. The radiological consequences for deposition of fallout into the sea are considerably smaller than in the case of terrestrial contamination. The probabilistic deposition pattern shows that the area in the direction of Kirkenes in Norway (west-north-west) has the lowest probability of being affected. Calculations show that *on average* about 80% of the released radioactivity will end up on Russian territory and/or in the Barents Sea. The danger of significant cross-border contamination during such an incident is thus fairly small. Nevertheless, such situations may occur, and the cross-border radiological consequences of a plausible worst-case scenario are presented below.

5.3.2 Plausible worst-case scenario for cross-border contamination

Although the probability is rather low, weather conditions during an incident may lead to contamination of foreign territory. To evaluate this situation, a Gaussian Puff model was used to compute the dispersion of radioactivity for stable weather (assuming “class D” atmospheric stability) with winds heading towards Kirkenes and the county of Finnmark in Norway. In the case of dry deposition only, the ^{137}Cs deposition at Kirkenes was then found to be close to 10 kBq/m^2; for the eastern part of Finnmark in general the ^{137}Cs deposition turned out to be one order of magnitude lower (typical value: 1 kBq/m^2). The deposition of ^{134}Cs and ^{90}Sr is a factor of ten and five lower, respectively. As a rule of thumb, the integrated air concentration (measured in kBq s/m^3) can be found by dividing the locally dependent deposition (kBq/m^2) by an average dry deposition velocity of 10^{-3} m/s. Deposition and integrated air concentration data were used as input for subsequent dose estimates for dry circumstances during the incident.

During rainfall the deposition of radioactivity is generally much larger, the precipitation rate during passage of the radioactive cloud being the most important parameter. Based on the statistical meteorological data for this region, wet deposition will on average lead to an estimated 25 times higher deposition compared to deposition under dry conditions. This value is typical for a moderate precipitation rate of about 1 mm/h; however, in the case of heavy or extreme rain showers, wet deposition may (locally) be a factor of 100 to 1000 times higher compared to dry deposition. This may cause hot spots in the track of the radioactive plume. As a result, rainfall during cloud passage may lead to contamination rates comparable to the situation in the middle of Sweden following the Chernobyl accident, but the affected area will be much smaller. Table 5.3 lists dose estimates valid for dry conditions, as well as estimates for the case of continuous moderate rainfall during the passage of the radioactive cloud.

5.3.3 Dose estimates for various pathways

In the early phase of an accident, that is, during and shortly after the passage of the radioactive cloud, members of the public are exposed to ionising radiation due to (1) inhalation of contaminated air, (2) external radiation from the cloud (cloud shine), and (3a) external radiation from radionuclides deposited on the ground and on surfaces (ground shine). Effective dose rates for the first 24 hours of exposure, derived from integrated air concentrations and deposition patterns (both for dry and wet conditions), were calculated for unprotected adults. “Worst-case” results for Kirkenes (about 110 km from the source) and the

Table 5.3. Maximum annual effective dose estimates for adult members of the public for two cross-border receptor areas assuming a "plausible worst-case" accident scenario. Kirkenes is considered to be an urban environment, whereas the results for the county of Finnmark refer to a critical group with a high consumption rate of locally obtained food products. "Short term" refers to the first 24 hours of the event (cloud passage); "long term" to the first year excluding the first 24 hours. "Wet" refers to the assumption of moderate rainfall during passage of the radioactive cloud.

		Kirkenes (urban)		Finnmark (rural)	
		Dry	Wet	Dry	Wet
	Physical data for ^{137}Cs				
	Ground deposition (kBq/m^2)	10 (c)	250 (c)	1	25
	Integrated air conc. (MBq s/m^3)	10	10	1	1
Time period	*Pathway of exposure*	*Effective dose (mSv)*		*Effective dose (mSv)*	
Short term (a)	Inhalation (b)	0.19	0.19	0.02	0.02
	Cloud-shine	—	—	—	—
	Ground-shine (short-term)	—	0.02	—	—
	Short-term subtotal	**0.19**	**0.21**	**0.02**	**0.02**
Long term	Ground-shine (long-term) (d)	0.08	1.9	0.02	0.50
	Ingestion (b)	0.03 (c)	0.9 (c)	0.19	4.5
	Long-term subtotal	**0.11**	**2.8**	**0.21**	**5.0**
First year	**Total annual dose**	**0.30**	**3.0**	**0.23**	**5.0**

(a) no protection assumed in the early phase of the incident
(b) effective dose commitment
(c) *average* contamination of the wider surroundings of Kirkenes is set equal to 30% of the Kirkenes value
(d) corrected for runoff (urban environment only) and shielding (rural area lower than urban environment)

eastern part of Finnmark (300–400 km from the source) are given in Table 5.3. Actual radiation doses may, however, be smaller, for instance, due to shielding effects (of buildings, for example). Since inhalation is the dominant pathway during cloud passage, then during this phase the difference between dry and wet weather conditions is insignificant. In either case, calculated dose rates are orders of magnitude smaller than internationally recommended intervention levels (in terms of avertable doses) for immediate protective actions, for example, sheltering (5–50 mSv) and evacuation (50–500 mSv) [ICRP, 1992; IAEA, 1996].

In the long term, radiation doses are received due to (3b) ground shine and (4) ingestion of contaminated food products (the inhalation dose following resuspension is neglected). External dose rates for the first year of exposure were estimated, taking into account the average effect of shielding by buildings, and, in the case of the urban environment of Kirkenes, runoff of deposited radioactivity [IAEA, 1994a]. The diet of people living in an urban environment in the northern part of Scandinavia consists mainly of imported food products, with the exception of a relatively small amount of lamb and reindeer meat (8 kg per capita per year altogether) and local berries and mushrooms (3 kg per year) [AMAP, 1997]. In order to estimate the ingestion dose for Kirkenes, it was assumed that local food products were obtained from surrounding areas having a ^{137}Cs deposition of on average 30% of the value for Kirkenes itself.

For the general Finnmark area, calculations were carried out for members of a so-called “critical group” with a much larger per capita intake of local products, namely, 120 kg per year of reindeer meat and 12 kg per year of berries [AMAP, 1997]. Aggregated transfer coefficients for radiocaesium were taken from [IAEA, 1994b]. Results of the dose calculations are shown in Table 5.3, both for dry and wet weather conditions. In the long term, there is a dramatic difference in expected radiation doses between dry and wet conditions during cloud passage. It should, in general, be noted that actual dose rates are highly dependent on the specific circumstances at the time of the accident. Especially in the Nordic area, there are strong seasonal effects (snow cover, grazing of animals etc.), all of which may influence the actual dose rate. For example, the radiocaesium transfer coefficient from surface contamination to activity concentration in reindeer meat may vary within one order of magnitude depending on available animal feed [Åhman and Nylén, 1997]. The estimated radiation doses should therefore not be considered to be the absolute truth; they are only indicators of the order of magnitude which may occur in case of a real accident.

The highest cross-border radiation dose that may be received in the first year following an accident that took place under dry weather conditions is estimated to be on the order of 0.3 mSv. This value may be compared to the limit of 1 mSv per year as proposed by the International Commission on Radiological Protection for exposure of the general public to anthropogenic sources [ICRP, 1991], as well as to the annual average effective dose to adults from natural sources of ionising radiation which is 2.4 mSv world-wide [UNSCEAR, 1993] and an estimated 3.2 mSv in Finnmark [Strand, 1998]. Rainfall during cloud passage results in significantly larger radiation doses, with external radiation being the dominant pathway of exposure for the urban environment of Kirkenes, and ingestion of local products such as reindeer meat for critical groups in the rural county of Finnmark.

It should be emphasised that radiation doses may be much higher in close vicinity of the accident, but an appropriate assessment of the local impact is beyond the “cross-border” scope of this study.

5.3.4 Discussion on atmospheric dispersion

In the above analysis of a given hypothetical accident involving a decommissioned nuclear submarine moored on the Kola Peninsula, some crude but conservative assumptions were made, for example, with respect to the release fraction of radionuclides from the reactor core. The derived reduced source term was two to three orders of magnitude smaller than that of the Chernobyl accident.

Probabilistic dispersion calculations show that the likelihood of radionuclide contamination of foreign territory is relatively low due to the prevailing south-southwestern winds. Even in the case of a radioactive plume heading directly towards Kirkenes in Norway (the least probable wind direction), short-term radiation doses well below 1 mSv are anticipated. As far as cross-border contamination is concerned, this implies that immediate actions such as sheltering or evacuation are not justified in the case of an accident with a decommissioned nuclear submarine. Long-term radiation doses are due to ingestion of contaminated food products and external radiation from deposited radioactivity. As long as weather conditions are dry during the passage of the radioactive cloud, the average individual effective radiation dose received in the first year will remain below 1 mSv, both for inhabitants of Kirkenes and for critical groups in the county of Finnmark. Rainfall during cloud passage may lead to enhanced deposition of radioactivity, which in turn will cause significantly higher long-term radiation doses. As a result, remedial actions for dose reduction may have to be considered. The probability of such a weather situation is, however, lower than one percent.

6 CONCLUSIONS AND RECOMMENDATIONS

This chapter summarises the findings of the preceding chapters and presents the conclusions and recommendations of the Pilot Study. It may be read independently of the rest of the report.

6.1 Summary

Among the four nations (France, Russia, the United Kingdom and the United States) that are currently decommissioning nuclear submarines, only Russia places non-defuelled, decommissioned submarines in floating storage for several years. As of 1995, there were about 50–70 such non-defuelled submarines at the Northern Fleet alone.

As described in the report, there are rigorous safety requirements in place governing the preparation of non-defuelled submarines for long-term storage afloat. Among the many conceivable accident scenarios, only *core heat-up events* (caused by a leak of coolant or by a loss of power to the pumps) and *criticality events* (caused by accidents or irregular procedures during defuelling) give rise to real concern. A core heat-up event will occur relatively slowly and most likely will remain confined to the reactor compartment. Since it depends on decay heat, which decreases with time, such an event can only occur at most a few years after reactor shut-down. The reactor vessel as well as the submarine hull itself are open to the air during defuelling. A rapid criticality accident will therefore lead to a release of radionuclides into the surrounding environment. On the order of one hundred TBq of ^{90}Sr and several hundred TBq of ^{137}Cs may be released to the air during such an accident (for comparison, the 1986 Chernobyl accident released an estimated 70 000 TBq of ^{137}Cs).

Dispersion modelling was performed for the hypothetical case of a criticality accident in the Ara Bay on the Kola Peninsula near the border between Russia and Norway. Several models were run to evaluate the consequences of a submarine sinking. In that case, any radionuclides released would be dispersed directly into the sea. If the reactor was undamaged, it was shown that the leakage rate to the bay would be insignificant and of negligible hazard, especially given the comparatively short period of time before the submarine would be refloated. If however the reactor compartment and the reactor primary circuit were breached and recovery was not instigated, activity released to the bay could be on the order of 2000 TBq per year, falling to 60 TBq per year after 10 years. Running a generic model of the circulation in the Ara Bay demonstrated that little of this material would leave the confines of the bay, the activity being taken up by the bottom sediments.

If radionuclides are released directly to the air, they may be rapidly distributed according to the current weather pattern. Specific calculations were made for a hypothetical accident again occurring in the Ara Bay on the Kola Peninsula. It was found that on average about 80% of the released radioactivity will fall on Russian territory and/or in the Barents Sea. A plausible worst-case calculation for Northeast Norway shows that even with winds heading directly towards Kirkenes, short-term radiation doses there are anticipated to correspond to well below one year of natural background radiation.

6.2 Conclusions

Long-term storage of non-defuelled, decommissioned nuclear submarines does not constitute good practice. Early defuelling completely eliminates the possibility of core recriticality, reduces the on-board radionuclide inventory by 90–99 % and significantly reduces supervision requirements. The remaining radioactivity is imbedded in the reactor materials and may only be released by corrosion, which is a very slow process. Furthermore, early defuelling reduces public anxiety over a situation generally perceived to be hazardous. The study nevertheless shows that the risk of cross-border radioactive contamination from the non-defuelled, decommissioned nuclear submarines found in Northwest Russia today is low. Rules and standard operating procedures are in place to prevent accidents from occurring. Provided that these rules and procedures are strictly followed, accidents should not occur. However, in the event that an accident nevertheless does occur, its consequences will generally be relatively small outside of a “local area,” the size of which depends on local topography and weather conditions.

Of the many possible accident scenarios discussed, only criticality accidents, loss-of-coolant/core heat-up accidents and hull damage due to sinking or ship collisions, for example, are considered to be potential causes of cross-border contamination. A criticality accident during defuelling is the kind of accident most likely to result in significant cross-border contamination. It is in this situation that the probability of damage to the fuel and release of radionuclides is highest. At the same time, the reactor core is open to the environment.

Core heat-up accidents may occur at any time in the event of a failure in the cooling system. Since the activity of the reactor core decreases with time, heat generation also decreases with time, and the potential consequences of a loss-of-coolant accident are therefore more serious soon after reactor shut-down. For first generation submarines, the period during which there is a significant risk of a core heat-up accident lasts approximately one year after reactor shut-down. Most decommissioned reactors have already been out of service for a longer period of time, and for these reactors core heat-up due to loss of coolant is not a concern. After one to three years of storage, the production of decay-heat is too low to melt the fuel even if the reactor is completely drained, making core heat-up accidents impossible. The integrity of the containment of the spent nuclear fuel as well as that of the fuel itself decreases with time, however, and this lower integrity may make defuelling at a later date both more difficult and more dangerous.

The sinking of non-defuelled submarines or collisions involving such submarines are unlikely to give rise to major releases of radionuclides. A study commissioned by the International Atomic Energy Agency (IAEA) determined that the rate of radionuclide releases from a number of submarine reactors that have been dumped in the Kara Sea are too low to be of serious concern. These release rates are still much higher than would be predicted if one of the non-defuelled, decommissioned submarines were to sink at her moorings. Before the reactors were dumped in the Kara Sea, the primary pipe work was cut out and caps welded on the open ends. Control rod drive mechanisms were removed, and the openings sealed. These seals are more likely to corrode away and admit seawater to the fuel inside the reactor pressure vessel earlier than would be the case for a fully shut-down reactor plant with all its high-pressure pipe work intact. The dumped units will also have many more reactor compartment penetrations, allowing the flow of seawater past the reactor itself; this would not be the case for a submarine sunken at the pier. Furthermore, submarines that have sunken at the pier can generally be recovered before much damage has taken place. Once a submarine has been defuelled, the risk of serious accidents is negligible. The reactor will still contain significant amounts of radionuclides, but these are imbedded in the reactor materials.

The content of radionuclides in a submarine reactor is much smaller than in a nuclear power plant reactor; hence under any circumstances, the release of radionuclides to the surrounding environment from a submarine reactor can only be a small fraction of that which was released during the 1986 accident at the Chernobyl nuclear power plant. At the same time it should be stressed that for the naval personnel involved in a submarine defuelling accident, the consequences may be very severe.

Should a release of radionuclides actually take place, the consequences beyond the immediate area will be more severe in the case of an atmospheric release than for a release into the sea. For an aquatic release, it is difficult to predict the exact dispersion and mixing mechanisms with much certainty due to the effects of wind shear on the surface and the lack of more precise hydrographical data. Estimated results for a submarine sinking in the Ara Bay suggest that the average dose in the first year to personnel working in small craft on the water in the vicinity of the sunken vessel may be on the order of 0.1 mSv/h. This level would fall to very low values by the entrance to the bay. Should recovery occur within the year, little of the activity would transfer to the Barents Sea.

As regards atmospheric releases of radionuclides from a decommissioned non-defuelled submarine on the Kola Peninsula, probabilistic dispersion calculations for the case of a criticality accident show that the likelihood of radionuclide contamination of foreign territory is relatively low due to the prevailing south-southwestern winds. Even in the case of a radioactive plume heading directly towards Kirkenes in Norway (the least probable wind direction), it is anticipated that the short-term radiation doses here will fall well below 1 mSv. As long as weather conditions are dry during the passage of the radioactive cloud, the average individual effective radiation dose received in the first year will remain below 1 mSv, both for inhabitants of Kirkenes and for critical groups in the county of Finnmark. Rainfall during cloud passage may lead to enhanced deposition of radioactivity, which in turn will cause significantly higher long-term radiation doses. As a result, remedial actions for dose reduction may have to be considered. The probability of such a weather scenario is, however, lower than one percent.

The handling of decommissioned submarines in general and the defuelling of their reactors in particular are difficult and potentially dangerous tasks that require well-defined rules and procedures as well as well-educated and motivated personnel. Accidents and incidents that have taken place over the years have led to some concern about current adherence to stated safety standards and the safety culture among the personnel who perform these tasks. A deeply embedded safety culture is crucial to the successful decommissioning of nuclear submarines.

6.3 General comment

It is important to note that even the “single problem” of non-defuelled, decommissioned nuclear submarines contains many elements. A system approach must therefore be adopted, that is, a comprehensive plan must be established that encompasses all required activities, from the securing of submarines awaiting defuelling to the defuelling operation itself, storage, transport and disposal of the spent nuclear fuel, as well as all the actions required to decommission and eventually dispose of the radioactive parts of the reactor and other submarine structures. Focusing on a few high-risk aspects without systematically addressing the other aspects in the chain of interlinked tasks is of little use and may even be counterproductive as it could potentially shift the high risk somewhere else and maybe even make it higher. The required activities themselves are not complex, but their safe and successful completion depends on the approaches taken during their execution.

6.4 Recommendations

1. In order to minimise the risk of accidents caused by human error, it is recommended that the procedures and rules for the many tasks entailed in the proper decommissioning and defuelling of nuclear submarines be rigorously enforced and regularly re-evaluated.

2. For the same reason, in order to minimise the risk of accidents caused by human error, it is recommended that high skill levels in the personnel involved be ensured and that a high safety culture be developed and maintained.

3. Early defuelling of nuclear submarines is generally good practice. It is recommended that decommissioned nuclear submarines be promptly defuelled as soon as proper on-land storage facilities are ready to accept the spent nuclear fuel.

4. Except for extreme cases of deterioration of fuel or containment, spent nuclear fuel is better kept inside a reactor than in other forms of temporary floating storage or inadequate land-based storage. However, in order to further reduce the risk of accidents, it is recommended that proper on-land facilities with sufficient capacity for interim storage of all spent nuclear fuel be constructed as soon as is reasonably possible.

5. Submarine reactors with damaged fuel present a number of complex challenges. The defuelling of such a reactor is complicated, and since different kinds of damage may have occurred, each reactor must be approached individually. It is recommended that the problems related to the decommissioning of submarines with damaged reactors be further studied.

6. The probability of cross-border contamination due to accidents involving non-defuelled, decommissioned submarines is low. However, given that the physical state of the vessels, their reactors and their nuclear fuel will continue to deteriorate over time, and as both the vessels themselves and the related problems will remain present for a number of years, it is recommended that an adequate monitoring programme is implemented to ensure the long-term safety of these vessels.

7. Although the cross-border radiological consequences of an accident with a non-defuelled, decommissioned nuclear submarine are limited, social and economic consequences as well as local-area consequences may be rather severe. It is therefore recommended that also for this reason efforts be made in order to reduce the risk of such accidents.

8. In order to minimise local-area consequences of an accident, it is recommended that neither the mooring of future non-defuelled, decommissioned nuclear submarines nor the defuelling of these vessels take place in the immediate vicinity of densely populated areas.

9. It is recommended that relevant safety information be exchanged internationally in order to foster good nuclear safety practices and techniques and to engender better assessments of nuclear safety issues.

10. In order to provide the general public with a realistic impression of the problems concerning non-defuelled, decommissioned nuclear submarines, it is recommended that safety issues regarding such submarines be addressed openly and frankly by those in possession of relevant information.

7 REFERENCES

Åhman and Nylén, 1997: B. Åhman and T. Nylén, *Transfer of radiocaesium from fallout to reindeer as an effect of diet composition.* Proc. Third International Conference on Environmental Radioactivity in the Arctic, Tromsø, Norway, June 1–5.

Ali *et al.*, 1997a: S. M. Ali, H. M. Beaumont, L. M. C. Dutton, B. J. Handy, M. Hosty, A. F. Parsons, S. P. Nielson, Y. Sivintsev, L. Lytsov, E. I. Yefimov, T. Sazykina, M. Zheleznyak, V. Maderich, N. Y. Nargvelashvily and L. Cecille, *The Radiological Consequences of the Marine Reactors Scuttled in the Kara Sea*. Proc. Third International Conference on Environmental Radioactivity in the Arctic, Tromsø, Norway, June 1–5.

Ali *et al.*, 1997b: S. M. Ali, H. M. Beaumont, L. M. C. Dutton, B. J. Handy, M. Hosty, A. F. Parsons, S. P. Nielson, Y. Sivintsev, L. Lytsov, E. I. Yefimov, T. Sazykina, M. Zheleznyak, V. Maderich, N. Y. Nargvelashvily and L. Cecille, *Evolution of the Radiological Situation Around the Nuclear Reactors which have been Scuttled in the Kara Sea*. Commission of the European Communities Study Contract B7-6340/95/000879/MAR/C3, Final Report, Three Volumes, NNC (UK) No. C5063/TR/001.

AMAP, 1997: Arctic Monitoring and Assessment Programme, *Arctic Pollution Issues: A State of the Arctic Environment Report (and underlying technical reports),* AMAP Report, Oslo, Norway.

ANL, 1963: *Reactor physics constants*. Report No. ANL-5800, Argonne National Laboratory, IL, USA, Second edition, Table 1–6.

Arkin and Handler, 1989: W. M. Arkin and J. Handler, *Naval Accidents 1945–1988*. Neptune Papers No. 3, Greenpeace/Institute for Policy Studies.

Bergman *et al.*, 1997: R. Bergman, L. Thaning and A. Baklanov, *Site-sensitive Hazards of Potential Airborne Radioactive Release from Sources on the Kola Peninsula.* Proc. Third International Conference on Environmental Radioactivity in the Arctic, Tromsø, Norway, June 1–5.

Blaauboer, 1995: R. O. Blaauboer, *SOIL_RAD – A computer program to calculate air kerma, ambient dose rate and effective dose rate due to photons emitted by radionuclides distributed in soil or on the soil-air surface.* RIVM Report No. 610064001, National Institute of Public Health and the Environment, Bilthoven, the Netherlands.

Burnham, 1986: J. U. Burnham, *Radiation Protection Point LePreau Generating Station*. New Brunswick Power, Canada.

Børresen *et al.*, 1998: S. Børresen, M. M. Sobieska and K. Gussgard, *Criticality Considerations on Russian Ship Reactors and Spent Nuclear Fuel*. Report No. TR/41.20.03, Scandpower A/S, Kjeller, Norway.

Chamberlain, 1991: A. C. Chamberlain, *Radioactive Aerosols.* Cambridge University Press, Cambridge, UK.

Dietrich, 1956: J. R. Dietrich, *Experimental Determination of the Self-Regulating and Safety of Operating Water-Moderated Reactors*. Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Vol. 13, pp. 88–101, United Nations, New York, NY, USA.

Dorrian, 1997: M. D. Dorrian, *Particle Size Distributions of Radioactive Aerosols in the Environment.* Radiat. Prot. Dosim. **69**(2), 117–132.

Dukert, 1973: J. M. Dukert, *Nuclear Ships of the World*. Coward, McCann & Geoghegan, Inc., New York, NY, USA.

Eriksen, 1990: V. O. Eriksen, *Sunken Nuclear Submarines*. Norwegian University Press, Oslo, Norway.

Griffiths *et al.*, 1956: P. Griffiths, C. W. Sill and M. Wilhelmsen, *Radiological Monitoring of a Nuclear Release.* Proc. of the International Conference on the Peaceful Uses of Atomic Energy, Vol. 13, pp. 119–121, United Nations, New York, NY, USA.

Handler, 1998: J. Handler, *The lasting legacy; Nuclear submarine disposal*. Jane's Navy International, January/February, pp. 12–20.

Hanf *et al.*, 1997: R. W. Hanf, G. P. O'Connor and R. L. Dirkes (Eds.), *Summary of the Hanford Site 1996 Environmental Report*. Report No. PNNL-11472-SUM, Pacific Northwest National Laboratory, Richland, WA, USA.

Harris *et al.*, 1993: J. R. W. Harris, R. N. Gorley and C. A. Bartlett, *ECOS II, An Estuarine Simulation Shell*. Plymouth Marine Laboratory, Plymouth, UK.

HMSO, 1997: *Admiralty Tide Tables Volume 1 European Waters*. N.P.201-97, Her Majesty's Stationery Office, London, UK.

Høibråten *et al.*, 1997: S. Høibråten, P. E. Thoresen and A. Haugan, *The sunken nuclear submarine Komsomolets and its effects on the environment*. The Science of the Total Environment **202**, 67–78.

House of Commons, 1989: Defence Committee, House of Commons, *Decommissioning of Nuclear Submarines,* Her Majesty's Stationery Office, London, UK.

IAEA, 1960: *Directory of Nuclear Reactors, Vol. III: Research, Test and Experimental Reactors*. Publication STI/PUB/22, International Atomic Energy Agency, Vienna, Austria.

IAEA, 1962: *Directory of Nuclear Reators, Vol. IV: Power Reactors*. Publication STI/PUB/53, International Atomic Energy Agency, Vienna, Austria.

IAEA, 1985: *Sediment Kd's and Concentration factors for Radionuclides in the Marine Environment*. Technical Report Series No. 247, International Atomic Energy Agency, Vienna, Austria.

IAEA, 1990: *The regulatory Process for the Decommissioning of Nuclear Facilities*. IAEA Safety Series No. 105, International Atomic Energy Agency, Vienna, Austria.

IAEA, 1994a: *Modelling the deposition of airborne radionuclides into the urban environment.* IAEA-TECDOC-760, International Atomic Energy Agency, Vienna, Austria.

IAEA, 1994b: *Handbook of parameter values for the prediction of radionuclide transfer in temperate environments.* IAEA Technical Reports Series No. 364, International Atomic Energy Agency, Vienna, Austria.

IAEA, 1996: *International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources.* IAEA Safety Series No. 115, International Atomic Energy Agency, Vienna, Austria.

IAEA, 1997a: *Predicted Radionuclide Release from Marine Reactors Dumped in the Kara Sea – Report of the Source Term Working Group of the International Arctic Seas Assessment Project (IASAP).* IAEA-TECDOC-938, International Atomic Energy Agency, Vienna, Austria.

IAEA 1997b: *Assessment of the Impact of Radioactive Waste Dumping in the Arctic Seas – Report of the International Arctic Seas Assessment Project (IASAP).* Executive Summary, LC.2/Circ.379, International Maritime Organization, London, UK.

IAEA, 1997c: *Radiological Conditions of the western Kara Sea: Assessment of the radiological impact of the dumping of radioactive waste in the Arctic Seas – Report of the International Arctic Seas Assessment Project (IASAP).* Radiological Assessment Reports Series, International Atomic Energy Agency, Vienna, Austria (in print).

IAEA, 1997d: *Draft Safety Guide on decommissioning of medical, industrial and research facilities*. Document NS-173, Division of Radiation and Waste Safety, International Atomic Energy Agency, Vienna, Austria.

ICRP, 1991: International Commission on Radiological Protection, *1990 Recommendations of the International Commission on Radiological Protection*. ICRP Publication No. 60, Annals of the ICRP **21**(1–3); Pergamon Press, Oxford, UK.

ICRP, 1992: International Commission on Radiological Protection, *Principles for Intervention for Protection of the Public in a Radiological Emergency*. ICRP Publication No. 63, Annals of the ICRP **22**(4); Pergamon Press, Oxford, UK.

van Jaarsveld, 1990: J. A. van Jaarsveld, *An operational atmospheric transport model for priority substances: specifications and instructions for use.* RIVM Report No. 222501002, National Institute of Public Health and the Environment, Bilthoven, the Netherlands.

van Jaarsveld, 1995: J. A. van Jaarsveld, *Modelling the long-term atmospheric behaviour of pollutants on various spatial scales*. Thesis, University of Utrecht, Utrecht, the Netherlands.

Jane’s 1997: *Jane’s Fighting Ships 1997–98*. Jane’s Information Group, Coulsdon, Surrey, UK.

Joint Committee on Atomic Energy, 1961: *SL-1 Accident.* Atomic Commission Investigation Board Report, Joint Committee on Atomic Energy, USA.

Khlopkin *et al.*, 1994: G. A. Gladkov, N. S. Khlopkin, V. N. Lystsov, G. A. Nejdanov, B. G. Pologikh and Y. V. Sivintsev, *Assessment and prognosis of the state of nuclear installation of submarine “Komsomolets”*. Report from Working Group under leadership of Academician N. S. Khlopkin, RRC “Kurchatov Institute”, Moscow, Russia (Distributed by the Norwegian Defence Research Establishment, Kjeller, Norway).

Khlopkin *et al.*, 1997: V. V. Elatomtsev, N. S. Khlopkin, V. N. Lystsov, B. G. Pologikh, Y. V. Sivintsev, A. S. Timonin and A. P. Zotov, *Nuclear Safety Assessment of Stored Afloat Non-defuelled Decommissioned Nuclear Submarines.* Report 31/8010, RRC "Kurchatov Institute," Moscow, Russia (Distributed by the Norwegian Defence Research Establishment, Kjeller, Norway).

Kocher, 1983: D. A. Kocher, *Dose rate conversion factors for external exposures to photons and electrons*. Health Phys. **45**(3).

Kocher and Sjoreen, 1985: D. C. Kocher and A. L. Sjoreen, *Dose rate conversion factors for external exposure to photon emitters in soil.* Health Phys. **48**(2), 193–205.

Kupca and Natalizio, 1997: *S. Kupca and A. Natalizio, Accident Risk Associated with Fuelled Decommissioned Nuclear Powered Submarines*. Presented at the NATO/Russian Academy of Sciences Advanced Research Workshop on "Analysis of Risks Associated with Nuclear Submarine Decommissioning, Dismantling and Disposal," Moscow, Russia, November 24–26.

Kværner, 1996: Kværner Moss Technology a.s, *Disposal of Russian Nuclear Submarines*., Contract No. 8085 with the Royal Ministry of Foreign Affairs, Oslo, Norway.

Natalizio, 1997: A. Natalizio, *Safety Analysis of Decommissioned Submarines*. Report No. AR-9704, ENSAC Associates Ltd., prepared for the Canadian Department of National Defence, Ottawa, Canada.

NATO, 1995a: *Cross-Border Environmental Problems Emanating from Defence-Related Installations and Activities, Phase I: 1993–1995, Volume 1: Radioactive Contamination*. NATO/CCMS Report No. 204, Brussels, Belgium.

NATO, 1995b: *Cross-Border Environmental Problems Emanating from Defence-Related Installations and Activities, Phase I: 1993–1995, Volume 2: Chemical Contamination*. NATO/CCMS Report No. 205, Brussels, Belgium.

NATO, 1995c: *Cross-Border Environmental Problems Emanating from Defence-Related Installations and Activities, Phase I: 1993–1995, Summary Final Report*. NATO/CCMS Report No. 206, Brussels, Belgium.

Naval Civil Engineering Laboratory, 1992: *Prediction of Pitting Corrosion Performance of Submarine Reactor Compartments After Burial at Trench 94, Hanford, Washington*. Naval Civil Engineering Laboratory, Port Hueneme, CA, USA.

NEA, 1995: *Chernobyl Ten Years on: Radiological and Health Impact*. OECD/NEA Committee on Radiation Protection and Public Health, Paris, France.

Nilsen and Bøhmer, 1994: T. Nilsen and N. Bøhmer, *Sources of Radioactive Contamination in the Counties of Murmansk and Arkhangelsk*, Report No. 1, The Bellona Foundation, Oslo, Norway.

Nilsen *et al.*, 1996: T. Nilsen, I. Kudrik and A. Nikitin, *The Russian Northern Fleet*. Report No. 2:1996, The Environmental Foundation Bellona, Oslo, Norway.

NRC, 1975: *Reactor Safety Study – an assessment of accident risks in U.S. commercial nuclear power plants (App. V)*. Report WASH-1400 (NUREG 75/014), United States Nuclear Regulatory Commission, Springfield, VA.

Ølgaard, 1993: P. L. Ølgaard, *Decommissioning of Naval Nuclear Ships*. Report No. NT-6 (Rev. 1), Department of Electrophysics, Technical University of Denmark, Lyngby, Denmark.

Ølgaard, 1994: P. L. Ølgaard, *Potential Risks of Nuclear Ships*. Report No. NT-11, Department of Electrophysics, Technical University of Denmark, Lyngby, Denmark.

Ølgaard, 1996a: P. L. Ølgaard, *Accidents in Nuclear Ships*. Nordic Nuclear Safety Research Report NKS/RAK-2(96)TR-C3, Denmark.

Ølgaard, 1996b: P. L. Ølgaard, *On reactivity accidents in nuclear submarines*, Report No. Risoe-I-1069(EN) , Risoe National Laboratory, Roskilde, Denmark.

Ølgaard, 1997: P. L. Ølgaard, *Nuclear Risks of Decommissioned Nuclear Submarines with Non-Defuelled Reactors*. Report No. Risoe-I-1207(EN), Risoe National Laboratory, Roskilde, Denmark.

Osipenko *et al.*, 1992: L. Osipenko, L. Giltsov and N. Mormul, *La dramatique histoire des sous-marin nucléaires soviétiques*. Robert Laffont, France.

OTA, 1995: *Nuclear Wastes in the Arctic: An Analysis of Arctic and Other Regional Impacts from Soviet Nuclear Contamination*. Report No. OTA-ENV-623, Office of Technology Assessment, Congress of the United States, through U.S. Government Printing Office, Washington, DC, USA.

Owrid and Collins 1990: G. M. A. Owrid and M. B. Collins, *The Barents Sea – An Oceanographic Literature Review I: General Introduction*. Hydrology, December.

Pavlov, 1997: A. S. Pavlov, *Warships of the USSR and Russia, 1945–1995*. Naval Institute Press, Annapolis, MD, USA.

Register of Shipping of the USSR: *Information of safety of icebreaker – transport lighter/containership with nuclear propulsion plant Sevmorput*. Approved by the Register of Shipping of the USSR (not dated).

Scott *et al.*, 1997: M. E. Scott, P. Gurbutt, I. Harms, R. Heling, Y. Kinehara, S. P. Neilson, I. Osvath, T. Sazykina, A. Wada and K.-L. Sjoeblom, *Radiological impact assessment of Dumped Waste in the Kara Sea*. Proc. Third International Conference on Environmental Radioactivity in the Arctic, Tromsø, Norway, June 1–5.

Seinfeld, 1985: J. H. Seinfeld, *Atmospheric chemistry and physics of air pollution*. Wiley Interscience, New York, NY, USA.

Shapiro, 1990: J. Shapiro, *Radiation Protection: A Guide for Scientists and Physicians*. Harvard University Press, Cambridge, MA, USA, Third edition.

Sivintsev, 1993: Y. Sivintsev, *Study of Nuclides Composition and Characteristics of Fuel in Dumped Submarine Reactors and Atomic Icebreaker "Lenin", Part I — Atomic Icebreaker*. RRC "Kurchatov Institute," Moscow, Russia.

Sivintsev, 1994: Y. Sivintsev, *Study of Nuclides Composition and Characteristics of Fuel in Dumped Submarine Reactors and Atomic Icebreaker "Lenin", Part II — Nuclear Submarines*. Report No. 31/7281, RRC "Kurchatov Institute," Moscow, Russia.

Smetsers *et al.*, 1994: R. C. G. M. Smetsers, H. Jeeninga, H. Slaper and R. O. Blaauboer, *Assessment and comparison of risks related to environmental radiological problems.* Contribution to the NATO/CCMS Pilot Study on Cross-Border Environmental Problems Emanating from Defence-Related Installations and Activities, Phase I.

Soyfer *et al.*, 1995: V. N. Soyfer, V. G. Makarov, E. A. Nurminsky, S. D. Malkin and A. A. Hrulev, *Analysis of the severe accident on the K-431 nuclear submarine*. Preprint No. IAE-5879/4, RRC "Kurchatov Institute," Moscow, Russia.

Strand *et al.*, 1997: P. Strand, A. I. Nikitin, B. Lind, B. Salbu and G. C. Christensen, *Dumping of Radioactive Waste and Radioactive Contamination in the Kara Sea; Results from 3 years of Investigations (1992–1994) in the Kara Sea*. Joint Norwegian-Russian Expert Group for Investigation of Radioactive Contamination in the Northern Areas, NRPA, Østerås, Norway, Second edition.

Strand, 1998: T. Strand, Norwegian Radiation Protection Authority, Østerås, Norway, private communication.

United Kingdom, 1996: *Statement to NATO CCMS study group on "The storage and disposal of decommissioned submarines in the UK."* Ref. RNC/NS/152/1/1, Royal Naval College, Greenwich, UK.

United States Navy, 1984: *Final Environmental Impact Statement on the Disposal of Decommissioned, Defueled Naval Submarine Reactor Plants.* United States Department of the Navy, Washington, DC, USA.

United States Navy, 1993: *U. S. Naval Nuclear Powered Submarine Inactivation, Disposal, and Recycling*. United States Department of the Navy, Washington, DC, USA.

UNSCEAR, 1988: United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), *Sources, effects and risks of ionizing radiation.* Report to the General Assembly with annexes, United Nations, New York, NY, USA.

UNSCEAR, 1993: United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), *Sources, effects and risks of ionizing radiation.* United Nations, New York, NY, USA.

Warden *et al.*, 1997: J. M. Warden, M. E. Mount and N. M. Lynn, *Possible Criticality of Marine Reactors Dumped in the Kara Sea*. Proc. Third International Conference on Environmental Radioactivity in the Arctic, Tromsø, Norway, June 1–5.

Yablokov *et al.*, 1993: A. V. Yablokov, V. K. Karasev, V. M. Rumyanstsev, M. E. Kokeev, O. J. Petrov, V. N. Lystsov, A. F. Emel'yanenkov and P. M. Rubtsov, *Facts and Problems related to Radioactive Waste Disposal in Seas Adjacent to the Territory of the Russian Federation*. Small World Publishers, Inc., Moscow, Russia.

Yefimov, 1994: E. Yefimov, *Radionuclides Composition, Characteristics of Shielding Barriers and Analysis of Weak Points of the Dumped Reactors of Submarine N601*. Institute of Physics and Power Engineering, Obninsk, Russia.

APPENDIX

A RADIONUCLIDE INVENTORY FOR THE *SEVMORPUT* REACTOR

This appendix presents calculated radionuclide inventories for the *Sevmorput* reactor under two different circumstances. The first case applies to normal operation for a given time at a given power level followed by a standard shut-down of the reactor; the second case is based on the first, but assumes a criticality accident five years after shut-down.

A.1 Decay following normal operation

Table A.1 and Table A.2 below list the inventory of actinides and fission products, respectively, for the *Sevmorput* reactor following normal operation at 50% power (67.5 MW_t) for 1.25 years. Table entries less than 37 Bq are indicated by a dash.

Table A.1. Actinide inventory in the Sevmorput *reactor (in Bq) as a function of time since shut-down.*

	Decay time			
Nuclide	0 days	90 days	1 year	5 years
Tl207	4.4E+03	6.4E+03	1.4E+04	1.1E+05
Tl208	6.1E+05	9.8E+05	2.2E+06	7.8E+06
Pb209	1.0E+02	1.0E+02	1.0E+02	2.4E+02
Pb211	4.4E+03	6.4E+03	1.4E+04	1.1E+05
Pb212	1.7E+06	2.7E+06	6.2E+06	2.2E+07
Bi211	4.4E+03	6.4E+03	1.4E+04	1.1E+05
Bi212	1.7E+06	2.7E+06	6.2E+06	2.2E+07
Bi213	1.1E+02	1.1E+02	1.1E+02	2.4E+02
Po211	1.1E+01	1.1E+01	1.1E+01	2.7E+02
Po212	1.1E+06	1.8E+06	4.0E+06	1.4E+07
Po213	1.0E+02	1.0E+02	1.0E+02	2.4E+02
Po215	4.4E+03	6.4E+03	1.4E+04	1.1E+05
Po216	1.7E+06	2.7E+06	6.2E+06	2.2E+07
At217	1.1E+02	1.1E+02	1.1E+02	2.4E+02
Rn219	4.4E+03	6.4E+03	1.4E+04	1.1E+05
Rn220	1.7E+06	2.7E+06	6.2E+06	2.2E+07
Fr221	1.1E+02	1.1E+02	1.1E+02	2.4E+02
Fr223	7.3E+01	7.3E+01	2.0E+02	1.6E+03
Ra223	4.4E+03	6.4E+03	1.4E+04	1.1E+05
Ra224	1.7E+06	2.7E+06	6.2E+06	2.2E+07
Ra225	1.2E+02	1.2E+02	1.2E+02	2.4E+02
Ac225	1.1E+02	1.1E+02	1.1E+02	2.4E+02
Ac227	5.3E+03	7.4E+03	1.6E+04	1.1E+05
Th227	4.7E+03	6.7E+03	1.5E+04	1.1E+05
Th228	1.7E+06	2.8E+06	6.2E+06	2.2E+07
Th229	3.2E+01	3.2E+01	3.2E+01	2.4E+02
Th230	2.3E+03	3.3E+03	6.2E+03	2.3E+04
Th231	8.9E+09	8.8E+09	8.8E+09	8.8E+09

Table A.1 (continued). Actinide inventory in the Sevmorput *reactor (in Bq) as a function of time since shut-down.*

Nuclide	Decay time			
	0 days	90 days	1 year	5 years
Th234	2.0E+08	2.0E+08	2.0E+08	2.0E+08
Pa231	2.5E+05	2.9E+05	4.4E+05	1.2E+06
Pa233	2.6E+09	3.1E+09	3.1E+09	3.1E+09
Pa234m	2.1E+08	2.0E+08	2.0E+08	2.0E+08
Pa234	1.1E+07	2.6E+05	2.6E+05	2.6E+05
U232	1.3E+07	1.5E+07	1.9E+07	2.9E+07
U233	5.0E+05	5.1E+05	5.2E+05	5.7E+05
U234	4.2E+08	4.2E+08	4.3E+08	4.8E+08
U235	8.8E+09	8.8E+09	8.8E+09	8.8E+09
U236	1.7E+10	1.7E+10	1.7E+10	1.7E+10
U237	1.6E+16	1.6E+12	1.5E+09	1.2E+09
U238	2.0E+08	2.0E+08	2.0E+08	2.0E+08
Np235	4.4E+07	3.7E+07	2.3E+07	1.8E+06
Np236	1.2E+04	1.2E+04	1.2E+04	1.2E+04
Np237	3.0E+09	3.1E+09	3.1E+09	3.1E+09
Np238	1.7E+15	6.2E+06	6.2E+06	6.1E+06
Np239	3.3E+16	4.0E+08	4.0E+08	4.0E+08
Pu236	5.8E+08	5.6E+08	4.7E+08	1.8E+08
Pu237	2.5E+09	6.3E+08	9.2E+06	—
Pu238	4.8E+12	5.0E+12	4.9E+12	4.8E+12
Pu239	6.9E+11	7.0E+11	7.0E+11	7.0E+11
Pu240	3.9E+11	3.9E+11	3.9E+11	3.9E+11
Pu241	6.5E+13	6.4E+13	6.1E+13	5.1E+13
Pu242	1.9E+08	1.9E+08	1.9E+08	1.9E+08
Am241	3.1E+10	5.7E+10	1.3E+11	4.9E+11
Am242m	1.4E+09	1.4E+09	1.4E+09	1.4E+09
Am242	9.8E+12	1.4E+09	1.4E+09	1.3E+09
Am243	4.0E+08	4.0E+08	4.0E+08	4.0E+08
Cm241	2.8E+02	4.2E+01	—	—
Cm242	2.4E+12	1.7E+12	5.3E+11	2.2E+09
Cm243	2.8E+08	2.8E+08	2.8E+08	2.5E+08
Cm244	8.7E+09	8.7E+09	8.4E+09	7.2E+09
Cm245	2.0E+05	2.0E+05	2.0E+05	2.0E+05
Cm246	9.8E+03	9.8E+03	9.8E+03	9.8E+03
Total	8.4E+16	7.3E+13	6.8E+13	5.7E+13

Table A.2. *Fission product inventory in the* Sevmorput *reactor (in Bq) as a function of time since shut-down.*

Nuclide	Decay time			
	0 days	90 days	1 year	5 years
H3	1.6E+13	1.6E+13	1.5E+13	1.2E+13
Be10	1.0E+05	1.0E+05	1.0E+05	1.0E+05
C14	4.2E+06	4.2E+06	4.2E+06	4.2E+06
Se79	2.5E+10	2.5E+10	2.5E+10	2.5E+10
Kr81	3.7E+02	3.7E+02	3.7E+02	3.7E+02
Kr85	4.4E+14	4.4E+14	4.1E+14	3.2E+14
Rb86	2.8E+13	9.9E+11	3.5E+07	—
Rb87	9.9E+05	9.9E+05	9.9E+05	9.9E+05
Sr89	1.0E+17	3.0E+16	7.0E+14	1.4E+06
Y89m	9.7E+12	2.8E+12	6.5E+10	9.2E+01
Sr90	3.8E+15	3.8E+15	3.7E+15	3.4E+15
Y90	3.9E+15	3.8E+15	3.7E+15	3.4E+15
Y91	1.3E+17	4.4E+16	1.7E+15	5.2E+07
Zr93	5.1E+10	5.1E+10	5.1E+10	5.1E+10
Nb93m	1.4E+09	1.9E+09	3.5E+09	1.1E+10
Nb94	1.6E+06	1.6E+06	1.6E+06	1.6E+06
Zr95	1.4E+17	5.2E+16	2.6E+15	3.6E+08
Nb95	1.4E+17	8.7E+16	5.7E+15	7.9E+08
Nb95m	1.5E+15	6.1E+14	3.1E+13	4.2E+06
Tc98	1.3E+04	1.3E+04	1.3E+04	1.3E+04
Mo99	1.3E+17	1.8E+07	—	—
Tc99	5.2E+11	5.2E+11	5.2E+11	5.2E+11
Tc99m	1.2E+17	1.8E+07	—	—
Rh102	1.7E+09	1.6E+09	1.4E+09	5.2E+08
Ru103	6.5E+16	1.3E+16	1.0E+14	6.5E+02
Rh103m	6.5E+16	1.3E+16	1.0E+14	6.5E+02
Ru106	5.1E+15	4.4E+15	2.6E+15	1.7E+14
Rh106	5.6E+15	4.4E+15	2.6E+15	1.7E+14
Pd107	4.3E+08	4.3E+08	4.3E+08	4.3E+08
Ag108	1.0E+08	1.4E+04	1.4E+04	1.4E+04
Ag108m	1.7E+05	1.7E+05	1.7E+05	1.6E+05
Ag109m	1.1E+15	4.0E+04	2.6E+04	2.9E+03
Cd109	4.6E+04	4.0E+04	2.6E+04	2.9E+03
Ag110	1.9E+14	3.4E+10	1.6E+10	2.7E+08
Ag110m	3.2E+12	2.5E+12	1.2E+12	2.0E+10
Ag111	4.7E+14	1.1E+11	—	—
Cd113m	3.6E+11	3.5E+11	3.4E+11	2.8E+11
In114	5.7E+09	1.1E+09	2.2E+07	—
In114m	3.9E+09	1.1E+09	2.3E+07	—
Cd115	1.7E+14	1.2E+02	—	—
Cd115m	1.0E+13	2.5E+12	3.5E+10	—
In115m	2.3E+14	2.8E+08	3.8E+06	—
Sn117m	5.5E+11	5.7E+09	4.6E+03	—
Sn119m	7.3E+11	5.9E+11	3.1E+11	9.7E+09
Sn121	2.8E+14	2.2E+10	2.2E+10	2.1E+10
Sn121m	2.9E+10	2.9E+10	2.9E+10	2.7E+10
Sb122	8.9E+12	8.3E+02	—	—
Sn123	3.4E+13	2.1E+13	4.8E+12	1.9E+09
Te123m	9.7E+09	5.7E+09	1.2E+09	2.5E+05

Table A.2 (continued). Fission product inventory in the Sevmorput *reactor (in Bq) as a function of time since shut-down.*

Nuclide	Decay time			
	0 days	90 days	1 year	5 years
Sb124	5.7E+12	2.0E+12	8.5E+10	4.2E+03
Sn125	2.0E+14	3.1E+11	7.9E+02	—
Sb125	1.7E+14	1.6E+14	1.3E+14	4.9E+13
Te125m	3.3E+13	3.7E+13	3.3E+13	1.2E+13
Sn126	8.3E+09	8.3E+09	8.3E+09	8.3E+09
Sb126	3.9E+12	2.7E+10	1.2E+09	1.2E+09
Sb126m	4.8E+12	8.3E+09	8.3E+09	8.3E+09
Sb127	2.7E+15	2.5E+08	—	—
Te127	2.7E+15	2.6E+14	4.4E+13	4.1E+09
Te127m	4.5E+14	2.6E+14	4.6E+13	4.2E+09
Xe127	3.1E+06	5.5E+05	2.9E+03	—
Te129	1.5E+16	3.0E+14	1.0E+12	—
Te129m	3.0E+15	4.7E+14	1.6E+12	—
I129	8.7E+08	8.8E+08	8.9E+08	8.9E+08
Xe129m	6.5E+10	5.9E+07	—	—
I131	6.2E+16	2.7E+13	1.3E+03	—
Xe131m	6.7E+14	1.1E+13	1.2E+06	—
Te132	9.2E+16	4.4E+08	—	—
I132	9.5E+16	4.6E+08	—	—
Cs132	1.3E+11	8.3E+06	—	—
Xe133	1.4E+17	1.2E+12	—	—
Xe133m	4.2E+15	3.0E+03	—	—
Ba133	9.6E+04	9.5E+04	9.0E+04	6.9E+04
Cs134	1.6E+15	1.5E+15	1.1E+15	3.0E+14
Cs135	2.3E+10	2.3E+10	2.3E+10	2.3E+10
Cs136	9.3E+14	8.1E+12	4.1E+06	—
Ba136m	1.0E+14	9.1E+11	4.6E+05	—
Cs137	3.8E+15	3.8E+15	3.7E+15	3.4E+15
Ba137m	3.6E+15	3.6E+15	3.5E+15	3.2E+15
Ce139	1.4E+09	8.7E+08	2.2E+08	1.4E+05
Ba140	1.4E+17	1.0E+15	3.2E+08	—
La140	1.4E+17	1.2E+15	3.7E+08	—
Ce141	1.2E+17	1.8E+16	5.1E+13	—
Ce142	1.0E+06	1.0E+06	1.0E+06	1.0E+06
Pr143	1.3E+17	1.4E+15	1.1E+09	—
Ce144	7.9E+16	6.3E+16	3.2E+16	9.3E+14
Pr144	7.9E+16	6.3E+16	3.2E+16	9.3E+14
Pr144m	1.1E+15	8.8E+14	4.5E+14	1.3E+13
Pm145	1.2E+08	1.6E+08	2.6E+08	3.3E+08
Sm145	5.3E+09	4.4E+09	2.5E+09	1.3E+08
Pm146	3.3E+10	3.2E+10	2.9E+10	1.8E+10
Sm146	6.0E+02	6.1E+02	6.7E+02	8.7E+02
Nd147	4.8E+16	1.6E+14	4.7E+06	—
Pm147	1.1E+16	1.1E+16	8.9E+15	3.1E+15
Sm147	4.7E+04	6.4E+04	1.1E+05	2.6E+05
Pm148	6.2E+15	1.8E+13	1.8E+11	—
Pm148m	1.6E+15	3.4E+14	3.4E+12	—
Pm149	2.8E+16	1.6E+04	—	—
Eu149	2.3E+04	1.2E+04	1.5E+03	—
Eu150	2.6E+05	2.5E+05	2.5E+05	2.3E+05
Sm151	2.6E+13	2.7E+13	2.6E+13	2.6E+13

Table A.2 (continued). Fission product inventory in the Sevmorput *reactor (in Bq) as a function of time since shut-down.*

Nuclide	Decay time			
	0 days	90 days	1 year	5 years
Eu152	2.2E+11	2.2E+11	2.1E+11	1.7E+11
Gd153	8.7E+10	6.7E+10	3.0E+10	4.6E+08
Eu154	5.0E+13	4.9E+13	4.6E+13	3.4E+13
Eu155	3.4E+13	3.3E+13	2.9E+13	1.6E+13
Eu156	1.5E+15	2.5E+13	8.8E+07	—
Tb160	1.4E+12	5.9E+11	4.2E+10	3.5E+04
Tb161	2.7E+12	3.2E+08	—	—
Ho166m	9.9E+04	9.9E+04	9.8E+04	9.8E+04
Er169	8.8E+06	1.2E+04	—	—
Tm170	2.4E+04	1.5E+04	3.4E+03	—
Tm171	4.7E+06	4.3E+06	3.2E+06	7.7E+05
Total	1.2E+19	4.3E+17	1.1E+17	1.9E+16

A.2 Decay following a criticality accident

The two tables in this section list the inventory of actinides and fission products, respectively, for the *Sevmorput* reactor following a criticality accident involving 10^{20} fissions. The accident occurs after five years of decay following normal operation at 50% power (67.5 MW_t) for 1.25 years (that is, the situation given by the last column in Table A.1 and Table A.2). Table entries less than 37 Bq are indicated by a dash.

Table A.3. Actinide inventory in the Sevmorput *reactor (in Bq) as a function of time after a criticality accident which occurs five years after shut-down.*

Nuclide	Decay time			
	0 minutes	1 minute	1 hour	1 day
Tl207	1.1E+05	1.1E+05	1.1E+05	1.1E+05
Tl208	7.7E+06	7.7E+06	7.7E+06	7.8E+06
Pb209	2.4E+02	2.4E+02	2.4E+02	2.4E+02
Pb211	1.1E+05	1.1E+05	1.1E+05	1.1E+05
Pb212	2.2E+07	2.2E+07	2.2E+07	2.2E+07
Bi211	1.1E+05	1.1E+05	1.1E+05	1.1E+05
Bi212	2.2E+07	2.2E+07	2.2E+07	2.2E+07
Bi213	2.4E+02	2.4E+02	2.4E+02	2.3E+02
Po211	2.7E+02	2.7E+02	2.7E+02	2.7E+02
Po212	1.4E+07	1.4E+07	1.4E+07	1.4E+07
Po213	2.4E+02	2.4E+02	2.4E+02	2.3E+02
Po215	1.1E+05	1.1E+05	1.1E+05	1.1E+05
Po216	2.2E+07	2.2E+07	2.2E+07	2.2E+07
At217	2.4E+02	2.4E+02	2.4E+02	2.4E+02
Rn219	1.1E+05	1.1E+05	1.1E+05	1.1E+05
Rn220	2.2E+07	2.2E+07	2.2E+07	2.2E+07
Fr221	2.4E+02	2.4E+02	2.4E+02	2.4E+02
Fr223	1.5E+03	1.5E+03	1.5E+03	1.5E+03
Ra223	1.1E+05	1.1E+05	1.1E+05	1.1E+05
Ra224	2.2E+07	2.2E+07	2.2E+07	2.2E+07
Ra225	2.4E+02	2.4E+02	2.4E+02	2.4E+02

Table A.3 (continued). Actinide inventory in the Sevmorput *reactor (in Bq) as a function of time after a criticality accident which occurs five years after shut-down.*

Nuclide	Decay time			
	0 minutes	1 minute	1 hour	1 day
Ac225	2.4E+02	2.4E+02	2.4E+02	2.4E+02
Ac227	1.1E+05	1.1E+05	1.1E+05	1.1E+05
Th227	1.1E+05	1.1E+05	1.1E+05	1.1E+05
Th228	2.2E+07	2.2E+07	2.2E+07	2.2E+07
Th229	2.4E+02	2.4E+02	2.4E+02	2.4E+02
Th230	2.3E+04	2.3E+04	2.3E+04	2.3E+04
Th231	8.8E+09	8.8E+09	8.8E+09	8.8E+09
Th233	5.5E+07	5.3E+07	8.4E+06	—
Th234	2.0E+08	2.0E+08	2.0E+08	2.0E+08
Pa231	1.2E+06	1.2E+06	1.2E+06	1.2E+06
Pa232	4.7E+06	4.7E+06	4.6E+06	2.8E+06
Pa233	3.1E+09	3.1E+09	3.1E+09	3.1E+09
Pa234m	2.1E+08	2.1E+08	2.0E+08	2.0E+08
Pa234	2.9E+05	2.9E+05	2.9E+05	2.6E+05
U232	2.9E+07	2.9E+07	2.9E+07	3.0E+07
U233	5.7E+05	5.7E+05	5.7E+05	5.7E+05
U234	4.8E+08	4.8E+08	4.8E+08	4.8E+08
U235	8.8E+09	8.8E+09	8.8E+09	8.8E+09
U236	1.7E+10	1.7E+10	1.7E+10	1.7E+10
U237	1.6E+12	1.6E+12	1.6E+12	1.4E+12
U238	2.0E+08	2.0E+08	2.0E+08	2.0E+08
U239	1.2E+15	1.2E+15	2.1E+14	—
Np235	1.8E+06	1.8E+06	1.8E+06	1.8E+06
Np236m	9.8E+06	9.8E+06	9.5E+06	4.7E+06
Np236	1.2E+04	1.2E+04	1.2E+04	1.2E+04
Np237	3.1E+09	3.1E+09	3.1E+09	3.1E+09
Np238	5.4E+11	5.4E+11	5.3E+11	3.9E+11
Np239	2.4E+11	5.0E+11	7.3E+12	6.7E+12
Np240	1.2E+06	1.2E+06	6.0E+05	—
Pu236	1.8E+08	1.8E+08	1.8E+08	1.8E+08
Pu237	5.1E+04	5.1E+04	5.1E+04	5.0E+04
Pu238	4.8E+12	4.8E+12	4.8E+12	4.8E+12
Pu239	7.0E+11	7.0E+11	7.0E+11	7.0E+11
Pu240	3.9E+11	3.9E+11	3.9E+11	3.9E+11
Pu241	5.1E+13	5.1E+13	5.1E+13	5.1E+13
Pu242	1.9E+08	1.9E+08	1.9E+08	1.9E+08
Pu243	5.3E+10	5.3E+10	4.6E+10	1.9E+09
Am239	3.4E+03	3.4E+03	3.2E+03	8.4E+02
Am240	7.9E+04	7.9E+04	7.8E+04	5.7E+04
Am241	4.9E+11	4.9E+11	4.9E+11	4.9E+11
Am242m	1.4E+09	1.4E+09	1.4E+09	1.4E+09
Am242	1.5E+11	1.5E+11	1.4E+11	5.4E+10
Am243	4.0E+08	4.0E+08	4.0E+08	4.0E+08
Am244	1.7E+09	1.7E+09	1.6E+09	3.2E+08
Cm242	2.2E+09	2.2E+09	2.2E+09	2.5E+09
Cm243	2.5E+08	2.5E+08	2.5E+08	2.5E+08
Cm244	7.2E+09	7.2E+09	7.2E+09	7.2E+09
Cm245	2.0E+05	2.0E+05	2.0E+05	2.0E+05
Cm246	9.8E+03	9.8E+03	9.8E+03	9.8E+03
Total	1.3E+15	1.3E+15	2.8E+14	6.6E+13

Table A.4. Fission product inventory in the Sevmorput *reactor (in Bq) as a function of time after a criticality accident which occurs five years after shut-down.*

Nuclide	Decay time			
	0 minutes	1 minute	1 hour	1 day
H3	1.2E+13	1.2E+13	1.2E+13	1.2E+13
Be10	1.0E+05	1.0E+05	1.0E+05	1.0E+05
C14	4.2E+06	4.2E+06	4.2E+06	4.2E+06
Ni66	2.0E+04	2.0E+04	2.0E+04	1.5E+04
Cu66	3.2E+04	3.0E+04	2.0E+04	1.5E+04
Cu67	3.1E+03	3.1E+03	3.1E+03	2.4E+03
Zn69	5.3E+04	5.3E+04	3.3E+04	5.0E+03
Zn69m	1.6E+04	1.6E+04	1.5E+04	4.7E+03
Ga70	1.3E+04	1.2E+04	1.8E+03	—
Zn71	3.1E+08	2.3E+08	—	—
Zn71m	1.7E+07	1.7E+07	1.5E+07	2.6E+05
Ni72	1.6E+11	1.7E+06	—	—
Cu72	3.6E+11	6.9E+08	—	—
Zn72	1.8E+08	2.0E+08	2.0E+08	1.4E+08
Ga72	8.0E+05	9.7E+05	1.0E+07	1.1E+08
Cu73	1.2E+12	2.3E+08	—	—
Zn73	1.8E+12	3.2E+11	—	—
Ga73	5.5E+09	7.8E+09	7.1E+09	2.7E+08
Ge73m	5.5E+09	7.7E+09	7.1E+09	2.7E+08
Zn74	3.1E+12	2.0E+12	—	—
Ga74	9.8E+10	1.4E+11	1.7E+09	—
Zn75	1.6E+13	2.2E+11	—	—
Ga75	7.8E+12	6.5E+12	2.2E+04	—
Ge75	5.8E+10	1.2E+11	1.8E+11	1.7E+06
Ge75m	2.4E+11	3.1E+11	1.7E+03	—
Zn76	4.2E+13	1.7E+10	—	—
Ga76	5.3E+13	1.6E+13	—	—
As76	1.8E+08	1.8E+08	1.8E+08	9.8E+07
Zn77	4.9E+13	3.4E+04	—	—
Ga77	1.1E+14	4.4E+12	—	—
Ge77	4.8E+10	6.4E+10	7.6E+10	1.8E+10
Ge77m	8.1E+13	5.1E+13	—	—
As77	1.8E+10	3.6E+10	5.5E+10	4.7E+10
Se77m	1.5E+09	2.1E+08	1.8E+08	1.5E+08
Ga78	2.3E+14	4.5E+10	—	—
Ge78	4.8E+12	5.0E+12	3.2E+12	6.0E+07
As78	7.0E+10	1.1E+11	1.5E+12	7.9E+08
Ga79	2.9E+14	1.4E+08	—	—
Ge79	6.4E+14	7.0E+13	—	—
As79	7.3E+13	8.8E+13	9.6E+11	—
Se79	2.5E+10	2.5E+10	2.5E+10	2.5E+10
Se79m	9.3E+12	2.2E+13	1.7E+12	—
Br79m	5.5E+07	6.6E+03	—	—
Ga80	1.7E+14	5.8E+02	—	—
Ge80	1.7E+15	4.0E+14	—	—
As80	1.8E+15	7.1E+14	—	—
Br80	1.4E+08	1.4E+08	2.0E+07	1.9E+05
Br80m	7.8E+06	7.7E+06	6.6E+06	1.8E+05
Ge81	2.0E+15	6.3E+12	—	—
As81	2.5E+15	8.4E+14	—	—

Table A.4 (continued). Fission product inventory in the Sevmorput *reactor (in Bq) as a function of time after a criticality accident which occurs five years after shut-down.*

	Decay time			
Nuclide	0 minutes	1 minute	1 hour	1 day
Se81	1.1E+14	1.6E+14	2.3E+13	1.7E+05
Se81m	3.5E+12	4.1E+12	2.1E+12	1.2E+05
81	3.7E+02	3.7E+02	3.7E+02	3.7E+02
Kr81m	2.3E+07	7.9E+05	—	—
Ge82	2.1E+15	1.5E+11	—	—
As82	3.3E+15	4.0E+14	—	—
As82m	1.3E+15	5.0E+13	—	—
Br82	3.6E+09	5.3E+09	1.8E+10	1.1E+10
Br82m	5.2E+12	4.6E+12	5.8E+09	—
Ge83	8.2E+14	7.7E+04	—	—
As83	5.4E+15	2.1E+14	—	—
Se83	2.0E+14	2.1E+14	3.3E+13	—
Se83m	2.6E+15	1.9E+15	—	—
Br83	1.5E+13	2.8E+13	5.6E+13	8.0E+10
Kr83m	6.4E+10	2.1E+11	1.7E+13	3.0E+11
As84	3.8E+15	1.4E+12	—	—
Se84	5.2E+15	4.3E+15	1.2E+10	—
Br84	1.2E+14	2.3E+14	1.9E+14	—
Br84m	7.5E+13	6.6E+13	7.2E+10	—
As85	2.4E+15	9.8E+05	—	—
Se85	7.4E+15	1.9E+15	—	—
Se85m	7.0E+15	7.0E+14	—	—
Br85	5.4E+15	5.7E+15	3.9E+09	—
Kr85	3.2E+14	3.2E+14	3.2E+14	3.2E+14
Kr85m	1.2E+13	2.7E+13	8.4E+13	2.3E+12
Se86	2.0E+16	1.1E+15	—	—
Br86	1.6E+16	1.0E+16	—	—
Br86m	4.1E+15	2.4E+11	—	—
Rb86	1.1E+09	1.1E+09	1.1E+09	1.1E+09
Rb86m	1.3E+12	6.4E+11	—	—
Se87	1.2E+16	4.7E+12	—	—
Br87	2.3E+16	1.1E+16	—	—
Kr87	3.6E+14	5.3E+14	3.8E+14	1.4E+09
Rb87	9.9E+05	9.9E+05	9.9E+05	9.9E+05
Sr87m	2.9E+08	2.9E+08	2.3E+08	7.8E+05
Se88	5.6E+15	1.1E+03	—	—
Br88	3.2E+16	2.3E+15	—	—
Kr88	3.7E+14	4.2E+14	3.3E+14	1.2E+12
Rb88	1.0E+14	1.1E+14	3.4E+14	1.4E+12
Br89	2.1E+16	9.1E+11	—	—
Kr89	2.4E+16	1.9E+16	4.7E+10	—
Rb89	1.3E+15	2.3E+15	5.0E+14	—
Sr89	1.9E+10	3.7E+10	1.2E+12	1.3E+12
Y89m	1.7E+10	1.1E+09	1.2E+08	1.2E+08
Br90	1.1E+16	1.3E+06	—	—
Kr90	7.1E+16	1.8E+16	—	—
Rb90	1.9E+16	2.2E+16	2.2E+10	—
Rb90m	4.4E+15	4.4E+15	3.5E+11	—
Sr90	3.4E+15	3.4E+15	3.4E+15	3.4E+15
Y90	3.4E+15	3.4E+15	3.4E+15	3.4E+15

Table A.4 (continued). Fission product inventory in the Sevmorput *reactor (in Bq) as a function of time after a criticality accident which occurs five years after shut-down.*

Nuclide	Decay time			
	0 minutes	1 minute	1 hour	1 day
Y90m	4.1E+08	4.1E+08	3.3E+08	2.2E+06
Kr91	5.3E+16	3.2E+14	—	—
Rb91	6.3E+16	3.4E+16	—	—
Sr91	9.0E+13	1.5E+14	2.0E+14	3.7E+13
Y91	5.3E+08	9.8E+08	6.1E+10	1.2E+12
Y91m	4.9E+11	1.5E+12	6.7E+13	2.3E+13
Kr92	2.7E+16	1.4E+06	—	—
Rb92	7.6E+16	5.5E+12	—	—
Sr92	7.0E+14	7.4E+14	5.7E+14	1.6E+12
Y92	7.1E+12	9.6E+12	1.2E+14	1.7E+13
Rb93	5.7E+16	2.7E+13	—	—
Sr93	1.5E+16	1.4E+16	5.8E+13	—
Y93	1.5E+13	2.7E+13	1.3E+14	2.8E+13
Zr93	5.1E+10	5.1E+10	5.1E+10	5.1E+10
Nb93m	1.1E+10	1.1E+10	1.1E+10	1.1E+10
Rb94	2.8E+16	2.5E+09	—	—
Sr94	6.1E+16	3.4E+16	—	—
Y94	2.8E+15	4.4E+15	7.8E+14	—
Nb94	1.6E+06	1.6E+06	1.6E+06	1.6E+06
Nb94m	2.1E+09	1.8E+09	2.7E+06	—
Sr95	8.0E+16	1.4E+16	—	—
Y95	8.7E+15	1.1E+16	2.3E+14	—
Zr95	7.0E+10	1.5E+11	1.4E+12	1.4E+12
Nb95	8.6E+08	8.6E+08	1.8E+09	2.8E+10
Nb95m	1.0E+08	1.0E+08	2.0E+08	2.8E+09
Y96	9.6E+16	6.5E+13	—	—
Nb96	8.4E+09	8.4E+09	8.2E+09	4.1E+09
Y97	7.7E+16	2.9E+11	—	—
Zr97	1.1E+14	1.1E+14	1.1E+14	4.3E+13
Nb97	3.6E+12	4.5E+12	5.1E+13	4.6E+13
Nb97m	7.1E+13	9.0E+13	1.0E+14	4.0E+13
Zr98	8.4E+16	2.1E+16	—	—
Nb98	8.4E+16	2.3E+16	—	—
Nb98m	8.4E+12	8.3E+12	3.7E+12	3.0E+04
Tc98	1.3E+04	1.3E+04	1.3E+04	1.3E+04
Y99	3.7E+16	4.2E+03	—	—
Zr99	8.8E+16	1.5E+08	—	—
Nb99	6.3E+16	4.0E+15	—	—
Nb99m	1.6E+16	1.2E+16	1.8E+09	—
Mo99	2.0E+13	2.7E+13	3.5E+13	2.7E+13
Tc99	5.2E+11	5.2E+11	5.2E+11	5.2E+11
Tc99m	2.5E+10	6.8E+10	3.3E+12	2.4E+13
Zr100	9.1E+16	1.9E+14	—	—
Nb100	9.9E+16	2.4E+14	—	—
Nb100m	3.2E+15	1.3E+09	—	—
Tc100	5.3E+15	3.3E+14	—	—
Zr101	4.8E+16	1.5E+07	—	—
Nb101	7.7E+16	2.0E+14	—	—
Mo101	6.2E+15	6.6E+15	4.0E+14	—
Tc101	2.5E+14	5.8E+14	1.1E+15	—

Table A.4 (continued). Fission product inventory in the Sevmorput *reactor (in Bq) as a function of time after a criticality accident which occurs five years after shut-down.*

Nuclide	Decay time			
	0 minutes	1 minute	1 hour	1 day
Zr102	3.6E+16	1.0E+10	—	—
Nb102	6.2E+16	1.9E+10	—	—
Mo102	7.5E+15	7.4E+15	2.0E+14	—
Tc102	7.1E+15	7.4E+15	2.0E+14	—
Tc102m	8.3E+12	7.0E+12	5.7E+08	—
Rh102	5.2E+08	5.2E+08	5.2E+08	5.2E+08
Nb103	3.5E+16	2.0E+05	—	—
Mo103	3.4E+16	1.8E+16	—	—
Tc103	1.9E+16	2.2E+16	—	—
Ru103	1.9E+11	4.7E+11	1.2E+12	1.2E+12
Rh103m	1.3E+09	5.4E+09	6.1E+11	1.2E+12
Zr104	1.8E+15	7.0E+07	—	—
Nb104	1.2E+16	1.5E+12	—	—
Mo104	2.0E+16	1.0E+16	—	—
Tc104	8.8E+14	1.4E+15	2.2E+14	—
Rh104	8.3E+15	3.0E+15	1.6E+10	—
Rh104m	2.0E+14	1.7E+14	1.3E+10	—
Nb105	4.1E+15	1.5E+09	—	—
Mo105	1.3E+16	4.0E+15	—	—
Tc105	1.5E+15	2.1E+15	1.1E+13	—
Ru105	3.3E+12	8.5E+12	7.0E+13	1.9E+12
Rh105	5.2E+08	2.2E+09	1.2E+12	6.8E+12
Rh105m	3.5E+11	1.2E+12	2.0E+13	5.3E+11
Mo106	6.0E+15	3.3E+13	—	—
Tc106	5.6E+15	2.2E+15	—	—
Ru106	1.7E+14	1.7E+14	1.7E+14	1.7E+14
Rh106	1.7E+14	1.7E+14	1.7E+14	1.7E+14
Rh106m	1.6E+09	1.6E+09	1.1E+09	7.3E+05
Ag106	2.0E+02	1.9E+02	—	—
Mo107	1.7E+15	6.1E+09	—	—
Tc107	2.1E+15	3.1E+14	—	—
Ru107	5.7E+14	6.4E+14	1.2E+10	—
Rh107	1.5E+13	3.5E+13	2.7E+13	—
Pd107	4.3E+08	4.3E+08	4.3E+08	4.3E+08
Pd107m	1.2E+13	1.6E+12	—	—
Tc108	5.9E+14	1.3E+11	—	—
Ru108	3.1E+14	2.7E+14	3.4E+10	—
Rh108	2.6E+14	2.8E+14	3.6E+10	—
Rh108m	2.6E+12	2.3E+12	2.5E+09	—
Ag108	5.0E+07	3.6E+07	1.4E+04	1.4E+04
Ag108m	1.6E+05	1.6E+05	1.6E+05	1.6E+05
Tc109	1.6E+14	3.7E+03	—	—
Ru109	6.1E+14	1.7E+14	—	—
Rh109	2.4E+14	3.0E+14	—	—
Rh109m	2.2E+14	1.8E+14	—	—
Pd109	2.3E+11	4.8E+11	1.8E+12	3.8E+11
Pd109m	5.1E+11	4.4E+11	7.1E+07	—
Ag109m	2.9E+11	3.5E+11	1.8E+12	3.8E+11
Cd109	2.9E+03	2.9E+03	2.9E+03	2.9E+03
Mo110	1.0E+12	1.4E+05	—	—

Table A.4 (continued). Fission product inventory in the Sevmorput *reactor (in Bq) as a function of time after a criticality accident which occurs five years after shutdown.*

Nuclide	Decay time			
	0 minutes	1 minute	1 hour	1 day
Tc110	4.5E+13	2.0E+05	—	—
Ru110	4.3E+14	2.3E+13	—	—
Rh110	5.1E+13	4.7E+07	—	—
Rh110m	4.3E+14	1.7E+14	—	—
Ag110	1.3E+14	2.3E+13	2.7E+08	2.7E+08
Ag110m	2.0E+10	2.0E+10	2.0E+10	2.0E+10
Tc111	1.2E+13	2.8E+03	—	—
Ru111	2.0E+14	1.4E+04	—	—
Rh111	3.3E+14	6.8E+12	—	—
Pd111	1.6E+13	1.8E+13	3.1E+12	1.4E+09
Pd111m	3.7E+10	3.7E+10	3.3E+10	1.8E+09
Ag111	2.4E+08	8.6E+08	3.4E+10	3.8E+10
Ag111m	6.0E+12	1.2E+13	3.3E+12	1.8E+09
Cd111m	7.2E+08	7.1E+08	3.1E+08	—
Ru112	1.1E+14	5.6E+08	—	—
Rh112	2.3E+14	9.7E+08	—	—
Pd112	2.9E+11	3.0E+11	2.9E+11	1.3E+11
Ag112	1.4E+09	2.5E+09	5.9E+10	1.6E+11
Ru113	5.0E+13	2.2E+07	—	—
Rh113	1.9E+14	1.2E+08	—	—
Pd113	1.5E+14	9.7E+13	3.0E+02	—
Ag113	3.0E+11	5.6E+11	9.4E+11	4.8E+10
Ag113m	1.3E+13	1.8E+13	2.1E+02	—
Cd113m	2.8E+11	2.8E+11	2.8E+11	2.8E+11
In113m	1.2E+02	1.2E+02	4.3E+01	—
Ru114	1.7E+13	8.0E+10	—	—
Rh114	1.1E+14	1.0E+11	—	—
Pd114	9.0E+13	6.9E+13	3.8E+06	—
Ag114	9.0E+13	7.1E+13	3.9E+06	—
In114	7.6E+09	4.1E+09	5.4E+05	5.3E+05
In114m	5.7E+05	5.7E+05	5.7E+05	5.6E+05
Rh115	4.9E+13	2.5E+11	—	—
Pd115	1.4E+14	4.9E+13	—	—
Ag115	4.6E+12	6.7E+12	1.0E+12	—
Ag115m	3.9E+13	2.1E+13	—	—
Cd115	9.8E+09	1.8E+10	6.3E+10	5.1E+10
Cd115m	7.7E+06	1.2E+07	1.4E+08	1.5E+08
In115m	1.6E+07	5.5E+07	7.1E+09	5.4E+10
Pd116	2.3E+14	7.3E+12	—	—
Ag116	8.3E+13	7.8E+13	1.8E+07	—
Ag116m	1.9E+13	2.9E+11	—	—
In116	1.4E+13	6.3E+11	—	—
In116m	1.3E+12	1.3E+12	5.9E+11	1.3E+04
Pd117	1.2E+14	2.0E+10	—	—
Ag117	5.4E+13	3.2E+13	—	—
Ag117m	8.4E+13	1.3E+11	—	—
Cd117	7.8E+11	1.0E+12	9.6E+11	1.6E+09
Cd117m	1.3E+11	1.6E+11	1.5E+11	1.3E+09
In117	2.9E+09	6.8E+09	2.2E+11	5.5E+09
In117m	3.4E+09	8.7E+09	3.0E+11	5.6E+09

Table A.4 (continued). Fission product inventory in the Sevmorput *reactor (in Bq) as a function of time after a criticality accident which occurs five years after shut-down.*

Nuclide	Decay time			
	0 minutes	1 minute	1 hour	1 day
Sn117m	4.7E+06	4.7E+06	5.6E+06	2.6E+07
Pd118	5.2E+13	3.7E+07	—	—
Ag118	1.1E+14	3.0E+09	—	—
Ag118m	7.5E+13	5.3E+07	—	—
Cd118	4.4E+12	4.6E+12	2.0E+12	1.1E+04
In118	4.2E+12	4.6E+12	2.0E+12	1.1E+04
In118m	1.7E+10	1.5E+10	1.5E+06	—
Pd119	3.8E+13	5.7E+02	—	—
Ag119	1.4E+14	3.2E+05	—	—
Cd119	5.2E+13	4.1E+13	1.0E+07	—
Cd119m	2.5E+13	1.8E+13	1.5E+05	—
In119	7.7E+12	1.3E+13	2.9E+10	—
In119m	1.7E+12	3.4E+12	1.0E+12	—
Sn119m	9.7E+09	9.7E+09	9.7E+09	9.7E+09
Pd120	1.6E+13	2.1E+08	—	—
Ag120	9.3E+13	3.0E+08	—	—
Cd120	1.5E+14	6.6E+13	—	—
In120	1.5E+14	7.0E+13	—	—
In120m	1.3E+12	4.9E+11	—	—
Cd121	2.0E+14	7.8E+12	—	—
In121	9.1E+12	1.9E+12	1.7E+07	—
In121m	4.8E+13	5.0E+13	1.3E+09	—
Sn121	4.3E+10	6.7E+10	1.9E+11	1.1E+11
Sn121m	2.7E+10	2.7E+10	2.7E+10	2.7E+10
Cd122	2.1E+14	5.1E+10	—	—
In122	2.4E+14	7.1E+10	—	—
In122m	1.4E+13	2.0E+11	—	—
Sb122	2.0E+09	2.0E+09	2.1E+09	1.7E+09
Sb122m	1.7E+11	1.4E+11	8.6E+06	—
Cd123	1.3E+14	9.8E+11	—	—
In123	1.5E+14	2.2E+12	—	—
In123m	3.2E+13	1.6E+13	—	—
Sn123	2.1E+09	2.1E+09	2.1E+09	2.1E+09
Sn123m	5.7E+12	6.7E+12	2.5E+12	4.1E+01
Te123m	3.5E+05	3.5E+05	3.5E+05	3.5E+05
In124	4.0E+14	4.9E+08	—	—
Sb124	7.8E+07	7.8E+07	7.9E+07	7.8E+07
Sb124m	6.6E+10	4.1E+10	—	—
In125	1.9E+14	2.6E+06	—	—
In125m	1.4E+14	4.0E+12	—	—
Sn125	1.4E+10	1.4E+10	1.4E+10	1.3E+10
Sn125m	4.1E+13	4.2E+13	5.7E+11	—
Sb125	4.9E+13	4.9E+13	4.9E+13	4.9E+13
Te125m	1.2E+13	1.2E+13	1.2E+13	1.2E+13
Sn126	8.3E+09	8.3E+09	8.3E+09	8.3E+09
Sb126	1.3E+09	1.3E+09	1.3E+09	1.3E+09
Sb126m	2.0E+11	2.0E+11	3.0E+10	8.3E+09
In127m	4.9E+14	4.3E+09	—	—
Sn127	7.5E+12	7.4E+12	5.4E+12	2.7E+09
Sn127m	3.2E+14	2.7E+14	1.4E+10	—

Table A.4 (continued). Fission product inventory in the Sevmorput *reactor (in Bq) as a function of time after a criticality accident which occurs five years after shutdown.*

Nuclide	Decay time			
	0 minutes	1 minute	1 hour	1 day
Sb127	6.1E+10	1.0E+11	3.5E+11	4.0E+11
Te127	4.3E+09	4.4E+09	2.2E+10	2.9E+11
Te127m	4.2E+09	4.2E+09	4.2E+09	4.6E+09
Sn128	1.2E+14	1.1E+14	5.7E+13	5.4E+06
Sb128	4.3E+11	4.3E+11	5.8E+11	1.5E+11
Sb128m	2.0E+13	2.6E+13	6.7E+13	6.5E+06
I128	2.7E+12	2.6E+12	5.1E+11	—
Sn129	1.9E+15	1.4E+15	1.4E+07	—
Sn129m	1.1E+15	9.5E+14	2.1E+12	—
Sb129	1.5E+13	2.2E+13	5.0E+13	1.3E+12
Te129	5.9E+11	7.5E+11	1.9E+13	1.5E+12
Te129m	1.6E+09	1.7E+09	9.2E+09	5.7E+10
I129	8.9E+08	8.9E+08	8.9E+08	8.9E+08
Xe129m	5.1E+06	5.1E+06	5.1E+06	4.7E+06
Sn130	5.1E+15	4.2E+15	7.0E+10	—
Sb130	1.2E+14	1.2E+14	4.3E+13	1.3E+03
Sb130m	1.5E+15	1.9E+15	1.2E+13	—
I130	2.1E+11	2.2E+11	3.5E+11	9.6E+10
I130m	1.5E+13	1.4E+13	1.5E+11	—
Sn131	1.2E+16	3.8E+15	—	—
Sb131	1.9E+15	2.0E+15	3.6E+14	—
Te131	1.2E+14	1.7E+14	6.3E+14	5.7E+11
Te131m	2.4E+12	2.5E+12	4.0E+12	2.5E+12
I131	1.3E+10	2.3E+10	2.4E+12	4.3E+12
Xe131m	3.7E+07	3.7E+07	6.6E+07	2.6E+09
Sn132	7.7E+15	2.6E+15	—	—
Sb132	5.6E+15	4.7E+15	2.7E+11	—
Sb132m	7.0E+15	6.5E+15	3.2E+09	—
Te132	8.2E+12	1.0E+13	1.8E+13	1.5E+13
I132	2.7E+12	2.7E+12	6.6E+12	1.5E+13
Cs132	1.3E+07	1.3E+07	1.3E+07	1.2E+07
Sn133	1.6E+15	9.4E+01	—	—
Sb133	1.5E+16	1.1E+16	8.7E+08	—
Te133	2.7E+15	3.2E+15	3.2E+14	4.0E+06
Te133m	1.1E+15	1.1E+15	5.6E+14	1.8E+07
I133	4.7E+12	7.0E+12	7.9E+13	5.0E+13
I133m	1.2E+15	1.2E+14	5.7E+13	1.8E+06
Xe133	9.1E+09	9.7E+09	3.0E+11	8.9E+12
Xe133m	1.6E+10	1.6E+10	3.7E+10	5.8E+11
Ba133	6.9E+04	6.9E+04	6.9E+04	6.9E+04
Sb134m	4.1E+15	6.1E+13	—	—
Te134	3.3E+15	3.2E+15	1.2E+15	1.4E+05
I134	2.5E+14	3.1E+14	1.2E+15	7.5E+07
I134m	1.6E+15	1.3E+15	2.0E+10	—
Xe134m	9.5E+14	3.1E+13	4.7E+08	—
Cs134	3.0E+14	3.0E+14	3.0E+14	3.0E+14
Cs134m	3.8E+12	3.8E+12	3.0E+12	1.3E+10
Sb135	2.3E+15	1.7E+04	—	—
Te135	5.0E+16	5.0E+15	—	—
I135	2.8E+14	3.2E+14	2.9E+14	2.6E+13

Table A.4 (continued). Fission product inventory in the Sevmorput *reactor (in Bq) as a function of time after a criticality accident which occurs five years after shutdown.*

	Decay time			
Nuclide	0 minutes	1 minute	1 hour	1 day
Xe135	3.2E+12	3.8E+12	3.0E+13	7.0E+13
Xe135m	2.3E+14	2.2E+14	5.9E+13	4.2E+12
Cs135	2.3E+10	2.3E+10	2.3E+10	2.3E+10
Cs135m	6.3E+11	6.2E+11	2.9E+11	4.2E+03
Ba135m	1.6E+09	1.6E+09	1.6E+09	9.0E+08
Te136	2.4E+16	1.9E+15	—	—
I136	2.8E+16	2.0E+16	3.3E+03	—
I136m	1.9E+16	7.5E+15	—	—
Cs136	4.7E+10	4.7E+10	4.7E+10	4.5E+10
Ba136m	5.3E+09	5.3E+09	5.3E+09	5.0E+09
Te137	6.6E+15	2.4E+10	—	—
I137	4.8E+16	8.2E+15	—	—
Xe137	2.4E+16	2.3E+16	5.3E+11	—
Cs137	3.4E+15	3.4E+15	3.4E+15	3.4E+15
Ba137m	3.2E+15	3.2E+15	3.2E+15	3.2E+15
I138	2.5E+16	2.9E+13	—	—
Xe138	8.6E+15	8.3E+15	4.6E+14	—
Cs138	2.9E+14	4.8E+14	1.6E+15	2.2E+02
Cs138m	9.1E+14	7.1E+14	5.5E+08	—
I139	1.5E+16	8.0E+07	—	—
Xe139	6.9E+16	2.3E+16	—	—
Cs139	8.3E+15	1.1E+16	1.5E+14	—
Ba139	7.0E+13	1.5E+14	1.1E+15	1.3E+10
Ce139	1.5E+05	1.5E+05	1.5E+05	1.5E+05
Pr139	3.6E+05	3.6E+05	3.1E+05	8.3E+03
Xe140	5.8E+16	2.3E+15	—	—
Cs140	5.8E+16	3.7E+16	—	—
Ba140	2.8E+12	4.8E+12	7.1E+12	6.6E+12
La140	3.8E+11	3.8E+11	5.0E+11	2.5E+12
Pr140	9.0E+08	7.2E+08	4.1E+03	—
Xe141	2.0E+16	2.0E+05	—	—
Cs141	6.6E+16	1.2E+16	—	—
Ba141	4.7E+15	5.8E+15	6.4E+14	—
La141	1.3E+13	3.0E+13	4.0E+14	7.8E+12
Ce141	1.2E+09	1.6E+09	2.6E+11	2.4E+12
Nd141	3.3E+06	3.3E+06	2.5E+06	4.1E+03
Cs142	4.2E+16	3.7E+05	—	—
Ba142	1.1E+16	1.0E+16	2.1E+14	—
La142	9.7E+13	1.8E+14	9.2E+14	2.6E+10
Ce142	1.0E+06	1.0E+06	1.0E+06	1.0E+06
Pr142	9.0E+11	9.0E+11	8.6E+11	3.7E+11
Cs143	2.3E+16	4.8E+05	—	—
Ba143	8.2E+16	4.1E+15	—	—
La143	6.8E+15	7.8E+15	4.3E+14	—
Ce143	2.3E+12	5.1E+12	5.7E+13	3.7E+13
Pr143	8.1E+07	2.2E+08	9.0E+10	2.4E+12
Ba144	7.0E+16	1.5E+15	—	—
La144	6.8E+16	3.2E+16	—	—
Ce144	9.3E+14	9.3E+14	9.3E+14	9.3E+14
Pr144	9.3E+14	9.3E+14	9.3E+14	9.3E+14

Table A.4 (continued). Fission product inventory in the Sevmorput *reactor (in Bq) as a function of time after a criticality accident which occurs five years after shut-down.*

Nuclide	Decay time			
	0 minutes	1 minute	1 hour	1 day
Pr144m	1.3E+13	1.3E+13	1.3E+13	1.3E+13
Ba145	2.9E+16	1.1E+12	—	—
La145	5.4E+16	1.0E+16	—	—
Ce145	1.5E+16	1.8E+16	2.4E+10	—
Pr145	2.4E+13	5.9E+13	2.1E+14	1.4E+13
Pm145	3.3E+08	3.3E+08	3.3E+08	3.3E+08
Sm145	1.3E+08	1.3E+08	1.3E+08	1.3E+08
Ba146	1.5E+16	3.4E+07	—	—
La146	3.8E+16	4.3E+13	—	—
Ce146	4.0E+15	4.1E+15	2.0E+14	—
Pr146	1.1E+14	2.3E+14	7.4E+14	—
Pm146	1.8E+10	1.8E+10	1.8E+10	1.8E+10
Sm146	8.7E+02	8.7E+02	8.7E+02	8.7E+02
La147	1.4E+16	6.8E+11	—	—
Ce147	2.5E+16	1.2E+16	—	—
Pr147	1.5E+15	2.4E+15	1.6E+14	—
Nd147	5.1E+10	1.4E+11	2.8E+12	2.7E+12
Pm147	3.1E+15	3.1E+15	3.1E+15	3.1E+15
Sm147	2.6E+05	2.6E+05	2.6E+05	2.6E+05
Ce148	1.8E+16	8.3E+15	—	—
Pr148	6.1E+15	7.8E+15	2.0E+08	—
Pm148	2.4E+11	2.4E+11	2.4E+11	2.1E+11
Pm148m	2.8E+10	2.8E+10	2.8E+10	2.7E+10
La149	9.1E+14	1.1E+07	—	—
Ce149	1.2E+16	2.7E+12	—	—
Pr149	6.8E+15	5.3E+15	7.2E+07	—
Nd149	5.1E+13	9.4E+13	1.4E+14	1.4E+10
Pm149	7.7E+09	2.5E+10	2.2E+12	5.3E+12
Ce150	4.3E+15	7.5E+10	—	—
Pr150	8.9E+15	1.4E+13	—	—
Pm150	4.7E+09	4.7E+09	3.6E+09	9.5E+06
Eu150	2.3E+05	2.3E+05	2.3E+05	2.3E+05
Pr151	4.2E+15	4.2E+14	—	—
Nd151	5.6E+14	6.2E+14	2.3E+13	—
Pm151	2.2E+11	4.8E+11	4.8E+12	2.8E+12
Sm151	2.6E+13	2.6E+13	2.6E+13	2.6E+13
Ce152	1.6E+14	5.3E+11	—	—
Pr152	1.5E+15	4.7E+12	—	—
Nd152	4.2E+14	4.1E+14	1.1E+13	—
Pm152	7.8E+13	1.3E+14	1.8E+13	—
Pm152m	1.1E+13	9.9E+12	4.3E+10	—
Eu152	1.7E+11	1.7E+11	1.7E+11	1.7E+11
Eu152m	2.9E+11	2.9E+11	2.7E+11	4.9E+10
Pr153	4.3E+14	2.5E+10	—	—
Nd153	1.5E+15	8.1E+14	—	—
Pm153	2.6E+14	3.7E+14	3.0E+11	—
Sm153	1.9E+12	2.0E+12	3.0E+12	2.1E+12
Gd153	4.6E+08	4.6E+08	4.6E+08	4.6E+08
Ce154	7.1E+11	2.5E+02	—	—
Pr154	5.7E+13	5.9E+02	—	—

Table A.4 (continued). Fission product inventory in the Sevmorput *reactor (in Bq) as a function of time after a criticality accident which occurs five years after shutdown.*

Nuclide	Decay time			
	0 minutes	1 minute	1 hour	1 day
Nd154	7.3E+14	2.4E+14	—	—
Pm154	3.5E+14	3.8E+14	2.4E+04	—
Pm154m	5.8E+13	4.4E+13	1.0E+07	—
Eu154	3.4E+13	3.4E+13	3.4E+13	3.4E+13
Nd155	2.2E+14	2.0E+13	—	—
Pm155	3.5E+14	1.8E+14	—	—
Sm155	1.5E+13	2.3E+13	5.1E+12	—
Eu155	1.6E+13	1.6E+13	1.6E+13	1.6E+13
Nd156	5.0E+13	5.4E+12	—	—
Pm156	1.6E+14	1.6E+13	—	—
Sm156	4.1E+11	4.9E+11	4.6E+11	8.5E+10
Eu156	2.7E+10	2.7E+10	2.8E+10	3.6E+10
Nd157	7.3E+12	1.6E+05	—	—
Pm157	3.8E+13	1.9E+13	—	—
Sm157	1.1E+13	1.2E+13	9.3E+10	—
Eu157	1.0E+10	2.0E+10	1.4E+11	5.0E+10
Nd158	7.5E+11	6.4E+04	—	—
Pm158	1.1E+13	1.3E+08	—	—
Sm158	9.7E+12	8.6E+12	5.1E+09	—
Eu158	2.3E+11	3.7E+11	6.3E+11	5.7E+02
Pm159	1.7E+12	7.6E+05	—	—
Sm159	5.3E+12	4.1E+12	1.1E+06	—
Eu159	4.7E+11	6.3E+11	1.4E+11	—
Gd159	2.5E+09	2.8E+09	2.0E+10	1.0E+10
Sm160	2.2E+12	1.2E+12	—	—
Eu160	3.2E+12	2.2E+12	—	—
Tb160	1.8E+07	1.8E+07	1.8E+07	1.8E+07
Sm161	4.5E+11	4.7E+07	—	—
Eu161	1.2E+12	4.5E+11	—	—
Gd161	3.7E+11	4.4E+11	7.6E+06	—
Tb161	2.2E+07	5.3E+07	2.5E+08	2.2E+08
Sm162	4.0E+10	9.5E+06	—	—
Eu162	9.5E+10	7.4E+10	2.0E+04	—
Gd162	5.0E+10	5.3E+10	6.7E+08	—
Tb162	5.0E+09	9.2E+09	2.9E+09	—
Tb162m	7.1E+07	7.1E+07	5.3E+07	4.1E+04
Eu163	5.3E+10	1.7E+08	—	—
Gd163	1.1E+11	7.4E+10	—	—
Tb163	5.6E+09	8.8E+09	1.9E+09	—
Gd164	3.4E+09	3.3E+09	5.0E+08	—
Tb164	7.0E+09	6.2E+09	5.8E+08	—
Gd165	1.4E+10	4.9E+09	—	—
Tb165	1.1E+10	1.0E+10	—	—
Dy165	3.9E+08	5.6E+08	7.2E+08	7.8E+05
Dy165m	3.8E+10	2.5E+10	3.9E+01	—
Dy166	1.1E+06	1.1E+06	1.0E+06	8.6E+05
Ho166	9.6E+06	9.5E+06	9.4E+06	5.6E+06
Ho166m	9.8E+04	9.8E+04	9.8E+04	9.8E+04
Er169	6.2E+02	6.2E+02	6.2E+02	5.8E+02
Er171	3.4E+04	3.4E+04	3.1E+04	3.7E+03

Table A.4 (continued). Fission product inventory in the Sevmorput *reactor (in Bq) as a function of time after a criticality accident which occurs five years after shut-down.*

Nuclide	Decay time			
	0 minutes	1 minute	1 hour	1 day
Tm171	7.7E+05	7.7E+05	7.7E+05	7.7E+05
Er172	4.1E+03	4.1E+03	4.0E+03	2.9E+03
Tm172	4.0E+01	4.0E+01	1.0E+02	8.7E+02
Nd156	5.0E+13	5.4E+12	—	—
Pm156	1.6E+14	1.6E+13	—	—
Sm156	4.1E+11	4.9E+11	4.6E+11	8.5E+10
Eu156	2.7E+10	2.7E+10	2.8E+10	3.6E+10
Nd157	7.3E+12	1.6E+05	—	—
Pm157	3.8E+13	1.9E+13	—	—
Sm157	1.1E+13	1.2E+13	9.3E+10	—
Eu157	1.0E+10	2.0E+10	1.4E+11	5.0E+10
Total	3.4E+18	7.4E+17	3.9E+16	2.0E+16

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